California Energy Commission

CONSULTANT REPORT

Codes and Standards Enhancement – Quality Demonstration Program

Appendices C-D

California Energy Commission

Gavin Newsom, Governor

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APPENDIX C:
Innovative Occupancy Sensors for Outdoor Applications

EXECUTIVE SUMMARY

Introduction

California Legislature mandates a reduction in lighting energy use for both commercial and residential sectors. Per Assembly Bill 1109, California must reduce its commercial outdoor lighting energy use by 25 percent between 2007 and 2018. This is also addressed federally by the U.S. Environmental Protection Agency (EPA) greenhouse gas reduction goals (EPA-2009 GHG) goals.

Optimized lighting achieved through the use of adaptive outdoor lighting systems has the potential to help reduce California outdoor lighting energy use. Occupancy-based lighting controls are clearly shown to be an effective strategy to mitigate energy waste and light pollution during long periods of inactivity generally associated with illuminated outdoor environments.

A key component to adaptive light systems is the sensor. However, existing PIR sensors applied in outdoor applications are simply indoor devices transferred to the outdoor environment. Many of these sensors have a fairly limited range of motion detection, usually up to distances equal to the mounting height of the sensor. While this detection range is effective for indoor applications, it is very limiting for outdoor applications, such as street lighting, which typically has much larger luminaire spacing and mounting heights. Moreover, traditional PIR sensors are often unable to accurately and consistently detect occupants moving at high speeds or under very hot or cold outdoor condition. Commercialized sensors appropriate for detecting occupancy under such conditions are emerging as stand-alone devices and/or as part of networked lighting control systems.

Project Purpose

The purpose of this research is to characterize the performance and reliability of innovative, outdoor occupancy sensors for street and parking applications. Research focuses on emerging, microwave sensing technology and wireless network control systems, which have the potential to meet the needs of hard-to-serve outdoor applications with tall pole heights and wide pole spacing.

Project Approach

This demonstration consisted of a series of laboratory and field evaluations to characterize sensor performance, quantify energy and other benefits, and understand additional technology development needs, if any, necessary to ensure reliable sensor operation under outdoor conditions. The approach to demonstrate and evaluate the system was conducted in the following steps: market analysis, potential economic impact analysis, demonstration site selection, technology selection, assessment plan development, technology implementation and pre and post retrofit data collection. Outcomes are evaluated with respect to energy use, system performance, end user feedback and cost effectiveness.

Project Results

The sensor captured all occupants and vehicles. For slow moving occupants and vehicles, the sensor, whet set at low gain, detected objects at approximately 10 feet and 70 feet, respectively. When the sensitivity was increased to high, the sensor's detection ranged improved to approximately 60 feet and 110 feet for pedestrians and cars, respectively. This represents a significant improvement over PIR technology, which is has a maximum detection range of approximately 50 feet under ideal conditions.

In a commercial roadway setting, a system owner can expect to achieve between three percent and 15 percent energy savings as compared to a system without adaptive controls. More aggressive commissioning of the system, such as shorter time out and implementing a high-end trim, results in higher savings. Tuning photocell settings can make a difference of up to 250 hours of system use per year, or approximately six percent per year variance, adding sizeable, unneeded energy consumption to a site. Aggressive timeout settings for occupancy sensors are expected to yield additional energy savings without compromising safety. It is recommended that the manufacturer consider this feature for development in the next generation of their product.

Installation labor is one of the biggest costs associated with an installation of an adaptive lighting control system. Training of installers and contractors is advised as the emerging technologies differ from the traditional street lighting products. Development of manufacturer installation manuals for adaptive systems are recommended to mitigate expensive installation issues.

With respect to end user acceptance of the deployed technology, the demonstration of innovative occupancy sensors in the field provided a test bed to survey end users regarding their satisfaction with static street lighting and adaptive street lighting systems. 54.5 percent of the end users surveyed use the space as drivers of motorized vehicles and 18.2 percent walk. Approximately 45 percent of respondents reported they are satisfied with the new lighting system for their task most frequently performed at the site. Forty-five percent of respondents reported they did not notice the adaptive control features of the demonstration site, that they were satisfied with the adaptive system and that they felt satisfied or highly satisfied with their feeling of safety while using the adaptive control system.

Chapter 1: Introduction

The California Legislature has mandated a reduction in lighting energy use for both commercial and residential sectors.[1] [2] Per Assembly Bill 1109, California must reduce its commercial outdoor lighting energy use by 25 percent between 2007 and 2018. Savings are also addressed federally by the U.S. Environmental Protection Agency (EPA) greenhouse gas reduction goals (EPA-2009 GHG)[3] goals.

A 2010 study estimates that roadway and parking lighting accounts for approximately 14.7 percent of national lighting energy consumption, with an estimated 97 million installed luminaires. Outdoor stationary lighting, composed of roadway and parking area lighting, accounts for approximately 87 percent of this use. The roadway sector reported 51 TWh annual energy consumption; and the parking sector reported 52 TWh of annual energy consumption.[4] The remaining 13 percent of the energy use in outdoor stationary lighting is comprised of sectors such as building exteriors, airfield lighting and billboard lighting.

Occupancy-based lighting controls are clearly shown to be an effective strategy to mitigate energy waste and light pollution during long periods of inactivity generally associated with illuminated outdoor environments. The California Lighting Technology Center (CLTC) with the support of the California Energy Commission (CEC) and Investor Owned Utilities (IOUs), has repeatedly and consistently demonstrated 50 to 60 percent energy savings with the use of occupancy-controlled, adaptive lighting for parking lots, parking garages, building perimeters and other related outdoor lighting applications.

Occupancy-based lighting controls have now been integrated into California's 2013 Building Energy-Efficiency Regulations (Title 24) for certain parking and outdoor areas. With this standard, most outdoor areas with luminaires mounted 24 ft. or less above grade must now utilize motion sensors to reduce light levels when areas are vacant.

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1 Assembly Bill 1109, the California Lighting Efficiency and Toxins Reduction Act (AB 1109, Huffman, Chapter 534, Statutes of 2007)

2 State of California, Assembly Bill 1109: *"California Lighting Efficiency and Toxins Reduction Act",* AB 1109, Huffman, Chapter 534, Statutes of 2007

3 More information on EPA goals may be found at http://www.epa.gov/oaintrnt/practices/eo13514.htm.

4 Navigant Consulting, Inc. "2010 U.S. Lighting Market Characterization." http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

In contrast, traditional outdoor lighting design practice has historically been limited to constant light output based on "worst case" conditions. This approach over-illuminates outdoor areas much of the time by providing maximum light output regardless of real-time requirements. Real-time requirements are dependent on the state of the space, which varies over time. Weather conditions, vehicle density, pedestrian traffic density, power supply quality, time of year, safety requirements and time of day all contribute to successful determination of the appropriate amount of light required for public spaces.

Optimized lighting achieved through the use of adaptive outdoor lighting systems have the potential to help reduce California outdoor lighting energy use. A key component to adaptive light systems is the sensor, which is used to provide stimuli to the lighting controllers and enable automatic light-level adjustments.

In practice, most sensor-controlled, exterior, adaptive lighting approaches use the integration of dimmable, LED lighting technology with passive infrared (PIR) motion sensors that allow the luminaire to adjust between 100 percent and 10 percent power depending on occupant activity. However, existing PIR sensors applied in outdoor applications are simply indoor devices transferred to the outdoor environment. Many of these sensors have a fairly limited range of motion detection, usually up to distances equal to the mounting height of the sensor. While this detection range is effective for indoor applications, it is very limiting for outdoor applications, such as street lighting, which typically has much larger luminaire spacing and mounting heights. Moreover, traditional PIR sensors are often unable to accurately and consistently detect occupants moving at high speeds or under very hot or cold outdoor conditions when the outer temperature of moving people is close to the temperature of outdoor objects.

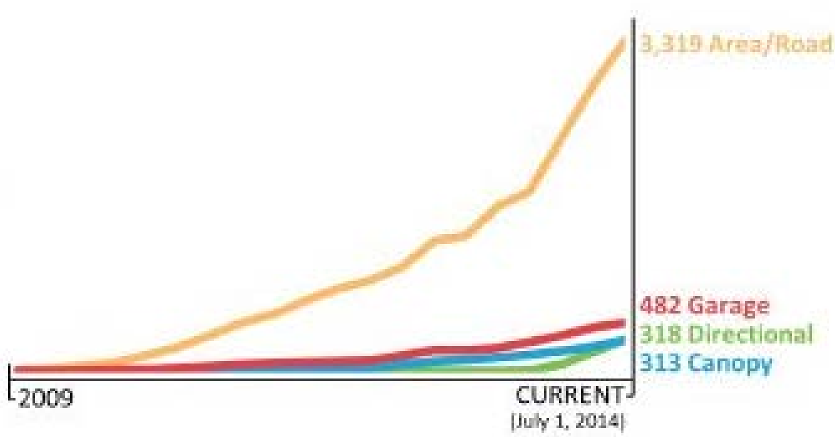
Commercialized sensors appropriate for detecting occupancy under such conditions are emerging as stand-alone devices and/or as part of networked lighting control systems. This report documents the demonstration of an innovative microwave occupancy sensor and radio-frequency (RF) control platform able to serve challenging outdoor lighting applications. Demonstration activities include market analysis, potential economic impact analysis, assessment plan development, technology deployment and pre and post-retrofit data collection to verify performance. The demonstrated technology is evaluated with respect to energy use, system performance and cost effectiveness.

Chapter 2: Market Assessment

A 2010 study estimates that the implementation of adaptive controls paired with dimmable outdoor fixtures could result in 39 to 60 percent energy savings over traditional lighting in the roadway sector, and 53 to 67 percent energy savings over traditional lighting in the outdoor area sector.[5]

While the data indicates nearly equal market share for both roadway and general outdoor area lighting energy use, municipality and state ownership trends in California show that roadway fixture ownership is far less distributed than general outdoor area lighting. This potentially allows new recommended roadway practices to affect faster change by addressing a larger number of outdoor fixtures through fewer system owners. For this reason, systems appropriate for the roadway application were prioritized during this demonstration. Since 2009, the outdoor lighting sector has shown significant growth in the number of outdoor light-emitting diode (LED) lighting products. Figure 1, provided by the US Department of Energy, shows the significant increase in outdoor LED products over the past five years.[6] LED luminaire developments show continuously increasing efficacy, high color rendering, and high power factors of luminaire drivers.

Figure 1: Outdoor LED Lighting Product Trends, 2009 – 2014



5 Lawrence Berkeley National Laboratory, LBNL-4998E; "Max Tech and Beyond." http://cltc.ucdavis.edu/sites/default/files/files/publication/2011_lbnl_max_tech_beyond.pdf

6 http://www1.eere.energy.gov/buildings/ssl/news_detail.html?news_id=21566

Source: Department of Energy CALiPER Report, July 2014

The lighting industry has started to address the use of adaptive control systems and innovative occupancy sensors in roadway applications through development of local and national standards. Both domestic [7] [8] and international [9] [10] roadway lighting stakeholder groups are recommending the use of LED sources citing their "high efficacy, even illumination and ability to integrate easily with controls" as desirable performance characteristics.

Recent product development efforts in the outdoor LED luminaire and lighting control industries have delivered commercialized technologies, ready to support adaptive networked lighting systems.

Based on the typical roadway lighting application, staff completed an economic analysis for the implementation of an adaptive roadway lighting system with innovative occupancy sensing. Staff used this analysis to understand the projected economic impact of implementing this strategy.

Staff completed lifecycle cost analysis (LCA) to determine the incremental net present dollar value (NPV), return on investment (ROI), and internal rate of return (IRR) of a hypothetical adaptive outdoor lighting system installed in a typical roadway application. The incremental NPV is provided to determine if the retrofit lighting technology will have a positive or negative cash flow for an assumed 15 year lifecycle analyzed. ROI is the return on investment divided by the cost of investment. This ratio is used to compare the efficiency of investment as compared to other scenarios.[11] IRR estimates the growth of investment options, with the highest IRR being most likely to return 'strong growth'.[12] To determine the IRR, an assumed finance rate of 8 percent and reinvestment rate of 3 percent are used. An assumed inflation rate of 4 percent is used for LCA calculations.

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7 MSSLC Lighting Control Task Force; PNNL-SA-102389; "Model Specification for Networked Outdoor Lighting Control Systems, Version 2.0"; April 28, 2014. http://energy.gov/eere/ssl/model-specification-networked-outdoor-lighting-control-systems

8 Northwest Energy Efficiency Alliance (NEEA); Report #40265, "Technology and Market Assessment of Networked Outdoor Lighting Controls"; June 30, 2011.

9 Institution of Lighting Professionals, UK; Technical Report, TR27 "Code of Practice for Variable Lighting Levels for Highways" - Advice and information on dimming and enhancement of road lighting levels; https://www.theilp.org.uk/resources/ilp-technical-reports/tr27/

10 E-street Project Report 05_157, Intelligent Road & Street lighting in Europe"; 2006-2008.

11 Return on Investment. www.investopedia.com. September 2015.

12 Internal Rate of Return. www.investopedia.com. January 2015.

Simple payback calculations were also added to the analyses. Simple payback is defined as the incremental investment (initial project costs) divided by the incremental annual cash flow[13], and is the number of years required to pay for the investment with the project savings.

Table 1 provides the economic analysis results comparing an HPS baseline system to a hypothetical LED adaptive system with 50 percent energy savings due to dimming during vacant periods. The economic analysis is based on the estimated 50 percent potential energy savings for varying energy rates, current material costs, estimated material useful life based on 10 year warranty, installation costs and typical outdoor street lighting maintenance practices as compared to a baseline HPS lighting system for a representative collector road.

Table 1: HPS Baseline vs. Hypothetical LED Adaptive System, based on 50 percent Energy Savings and Current Material Cost Quotes

Energy Price per kWh ($)	**$0.0824**	**$0.1000**	**$0.1200**	**$0.1400**	***$0.15046***	**$0.1600**	**$0.1800**	**$0.2000**	**$0.2200**
ROI	-0.05	0.05	0.17	0.29	*0.36*	0.42	0.54	0.66	0.78
IRR (%)	3.2%	3.9%	4.7%	5.4%	*5.7%*	6.0%	6.6%	7.2%	7.7%
Simple Payback (Years)	21.5	17.7	14.8	12.7	*11.8*	11.1	9.9	8.9	8.1
Incremental NPV ($)	-$815	$845	$2,732	$4,619	*$5,606*	$6,507	$8,394	$10,281	$12,168

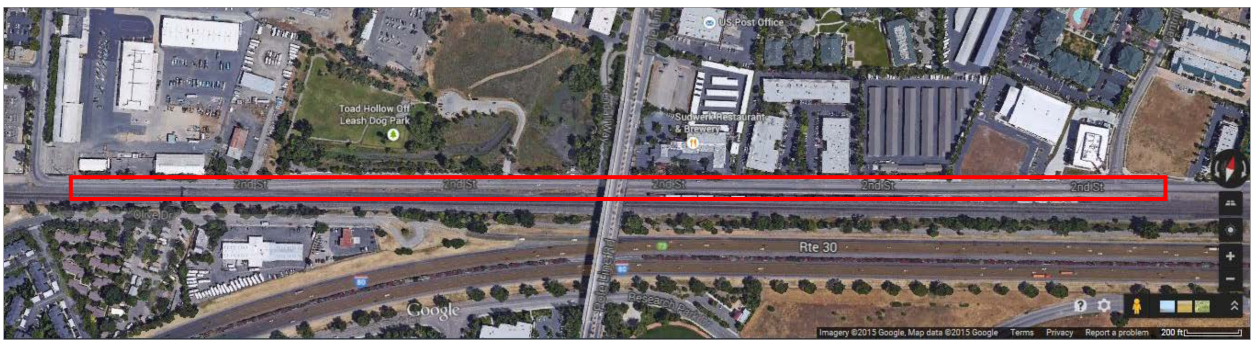
Source: CLTC

13 IES “Recommended Practice for the Economic Analysis of Lighting”, RP-31-14.

Chapter 3: Technology Demonstration

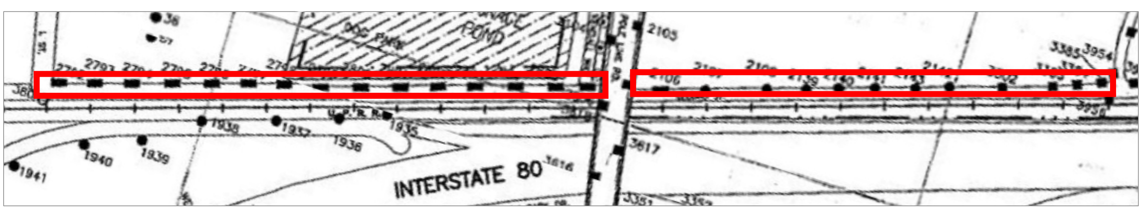
The demonstration site is located on a collector street in Yolo County, California, as shown in Figure 3 provides pole locations for the 26 luminaires included in the demonstration site. Fourteen poles are west of the overpass and 12 poles are east of the overpass. Each of the poles is 28 feet tall, with a six foot long tenon. Poles are spaced from 140 to 165 feet apart.. The site is approximately 0.7 miles long and runs parallel to a major interstate highway. The test bed is divided in two sections (West and East) by a pedestrian overpass. Figure 3 provides pole locations for the 26 luminaires included in the demonstration site. Fourteen poles are west of the overpass and 12 poles are east of the overpass. Each of the poles is 28 feet tall, with a six foot long tenon. Poles are spaced from 140 to 165 feet apart.

Figure 2: Second Street in Davis, California



Source: Google Maps

Figure 3. Second Street, Top View



Source: City of Davis

The demonstration site is located in Northern California Central Valley, inland of the Bay Area, and is associated with California climate zone 12. Stockton is the reference city for Zone 12. 14

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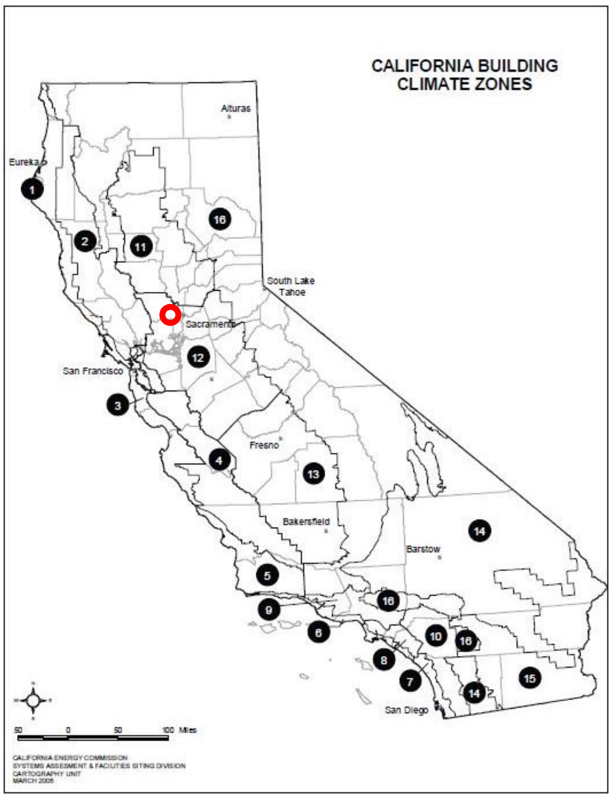
14 More local, climate zone information may be found at http://www.pge.com/includes/docs/pdfs/about/edusafety/training/pec/toolbox/arch/climate/california_climate_zone_12.pdf.

Except for the relatively high temperatures in the summer with periods of over 90 degrees Fahrenheit (˚F) from July through September, no extreme climate events are typical for the demonstration area. Climate zone maps and other site condition data is provided in Figure 4.

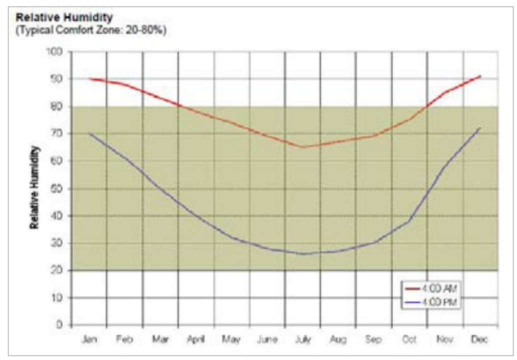
The California Energy Commission (Commission) provides wind speed reference maps. The mean annual wind speed is 11.2 mph (5.0m/s) for Yolo County per 2006 wind speed maps. The poles at the demonstration site are 28 feet tall, or 8.5 meters. Based on the expected wind at 30 meters, wind induced pole sway is not expected as a significant source contributing to false occupancy triggers.

Figure 4: Climate Data - Demonstration Site

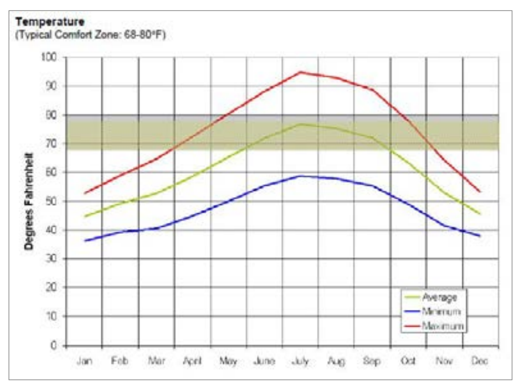
Climate Zones



Annual Humidity - Site



Annual Temperature - Site



Sources: Left: CEC, 2013 Building codes Section 100.1-A; Right: PG&E Climate zones

The demonstration site contains one traffic lane and one bicycle lane in each direction. The street has a maximum allowed speed of 45 miles per hour (mph) with limitations lowering to 35, 25 and down to 15 mph as you near the west corner of the site. A walkway for pedestrians is located on the north side of the street. A berm is located near the east end of the site, with the berm tapering off away from the intersection of the site and a connecting street.

A large section of public parking is provided along the road, located from the overpass towards west end of the site. The curb along the south side of the demonstration site is directly adjacent to an Amtrak train track, part of the *Capitol Corridor* train route. No shoulder is available for either the north or the south side of the street, barring the bicycle lanes. A median is present for the road section between the east intersecting street and the overpass.

The existing luminaires at the demonstration site are dimmable BetaLED STR-LWY LED luminaires (since acquired by Cree). Each luminaire has a system wattage of 94 Watts and is powered by 120 AC voltage service 24 hours per day, 7 days per week. Control of the existing system is through a networked control system using photoelectric control units (widely referred to as "photocell" [15]) in combination with a twist-lock, or ANSI C136.10[16], receptacle.

Standard photocells are light sensitive relays with pre-sets to turn a fixture ON at sunset and OFF at sunrise. A typical setting to determine sunset is when the photocell detects less than 70 lux. Sunrise is defined as when more than 35 lux is detected. Photocell settings can make a difference of up to 250 hours per year, or approximately six percent per year variance, adding sizeable consumption to an installation.

Typical stand-by, or vampire load, of a photocell is between 0.25 Watts and 5 Watts. The networked photocell used in the demonstration site has a stand-by load of 1.5 Watts, or approximately 13.2 kWh per year. Assuming that the network control system has constant connection to the head-end software with no errors, accuracy levels for timing and switching can be disregarded for the product used on the demonstration site because it has a geolocation time clock feature.

15 http://www.cosine.co.za/images/Publications/Streetlight%20photocell%20research.pdf. Ian McLaren.

16 ANSI C136.10-2006, three connector standard

Figure 5: Existing LED Light Fixtures at Demonstration Site

Source: ADM Associates

Figure 6: Left, Pole Identification Number; Right, Lighting at Dusk

Source: ADM Associates

Fixture poles with surrounding trees typically result in blocked occupancy sensors. These poles have been identified and excluded from the energy use measurement and verification process. No other landscaping details have been identified to affect system functionality.

Inspection by the project team during a site walk indicates that traffic density increases at intersections, along the restaurant entrance next, the dog park entry path and nearing the southernmost street corner. Anticipated occupant types in the demonstration site are motor driven vehicles such as large trucks, busses, large delivery transporters, shuttle services, automobiles, motorcycles, as well as bicycles and pedestrians (both walking and jogging).

Most nearby shops and businesses have typical business hours, except for one local restaurant, a dog park, and a fueling station. The restaurant closes on work days between 9:00 pm to 9:30 pm, and weekends at 10:30 pm. The dog park is open until early evening. The fueling station, being used by local shuttle busses servicing Sacramento Airport to refuel, operates 24 hours per day, seven days per week. Local police headquarters are located nearby and patrolling vehicles may lead to higher traffic along the demonstration when shift changes occur through the day.

No routine events affected the operating schedule during the monitoring period and there were no road work or similar construction activities conducted at the demonstration space during the monitoring period.

Technology Selection

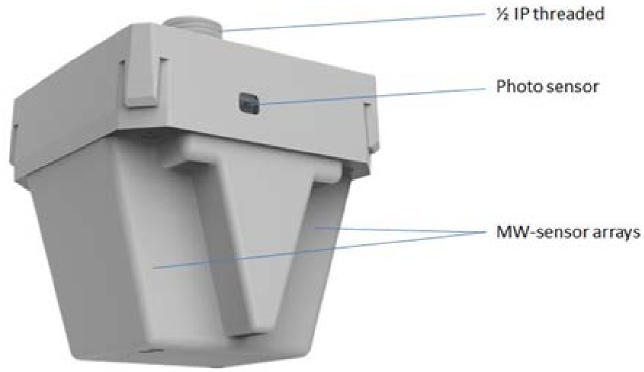
The demonstration site provided luminaires, as previously detailed, that are *controls-ready*. The necessary infrastructure to add sensors and networking capabilities was in place.

Occupancy Sensors

Occupancy sensors, also called motion sensors, are an important component in advanced outdoor lighting control systems. They play a critical role in automatically adapting lighting to application/task appropriate light levels during occupied periods and reducing that lighting when it's not needed. To date, sensors predominantly marketed for outdoor applications have been passive infrared (PIR) technology. PIR technology has inherent limitations including limited detection range, limited reliability in hot climates, and reduced detection accuracy of high speed objects. Microwave sensing technology is a new addition to the outdoor market.

The occupancy sensor selected for this demonstration is the microwave (*MWX-LVE-180U* Generation 3) from Lumewave/Echelon Corporation, shown in Figure 7. At the time of the demonstration, the selected solution was a prototype product. The product became commercially available beginning mid-2015. Full product specifications are provided in Appendix A.

Figure 7. Microwave Sensor, Lumewave MWX-LVE-180U



Source: Lumewave/Echelon

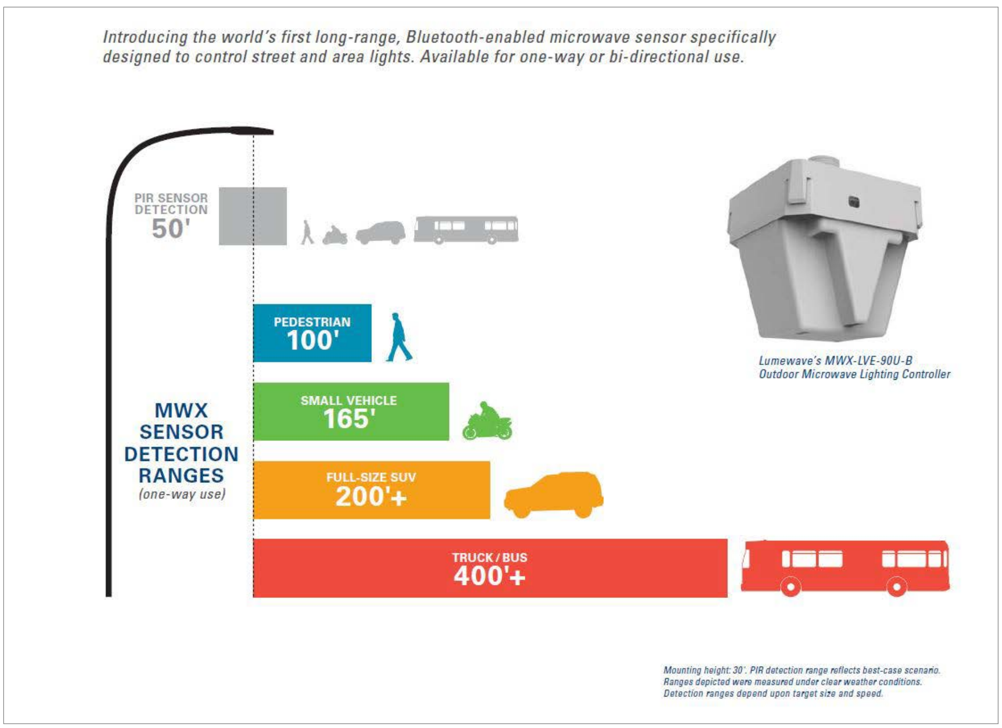
The selected sensor works in the X-Band, or microwave/high-frequency, with 10.25 GHz technology via FFT Doppler based *Doppler radar* (FCC certified). No other high-frequency sensors specifically marketed for outdoor street lighting applications and with similar functionality were identified in the U.S. market. Two similar European products were identified however, neither were available to the U.S. market at the time of this demonstration.

The sensor has a physical size of approximately 3.5 cubic inches. The sensor is shown in Figure 7 with a threaded straight mounting base; there are other mounting options are available. Two discrete motion sensor modules are contained within the housing. These sensor modules can be used as one-way or two-way detectors by using one or two modules, respectively. In addition to occupancy detection capabilities, the sensor contains two photosensors to extinguish luminaires during daytime hours. The photosensors can be disabled though the controls interface as needed.

The sensor has an outdoor ingress protection rating of IP65 for dust and water jet protection. [17] The sensor can be used with a Lumewave-specified power pack as a stand-alone sensor to control one 0-10 V driver; or in conjunction with a wireless radio frequency (RF) control system.

Figure 8 contains marketing literature comparing the detection range of the demonstrated sensor to a PIR sensor. The top gray block depicts the standard PIR sensor range of approximately 50 feet. The colored ranges depict the microwave sensor's anticipated detection range for various occupant types based on size of the object. The larger the frontal silhouette of the occupant, the further away the sensor can detect the occupant. The demonstrated microwave sensor has a speed sensitivity range from 0.2 to 99.0 miles per hour (mph).

Figure 8: Sensor Detection Range



Source: Lumewave/Echelon

17 "IP - Ingress Protection" code, International Standard IEC 60529

The demonstrated sensor utilizes Bluetooth-4.0 technology to remotely configure settings wirelessly. This is an improvement to dip-switch settings which require the commissioning agent to be at the sensor, typically requiring a bucket truck for access. Figure 9 shows an example of a Bluetooth 4.0 enabled smartphone and the demonstrated control system's application software[18]. Eleven settings are available to adjust the sensors detection range and the control of the luminaire, shown in Table 2.

Motion detection signals from both sensor modules are manipulated and transferred via internal control circuitry to a secondary device that controls the output level of the luminaire. This is true for both the stand-alone power pack with the presets defined via Bluetooth settings; and in combination with the RF control system.

Figure 9: Remote Commissioning Interface

Source: Lumewave

Table 2. Sensor Control Feature Settings

Control Feature	Setting Options
Sensitivity for direction A	Low / Med / High
Sensitivity for direction B	Low / Med / High
Motion output filter	"Pedestrian" < 6mph / 6mph < "Traffic" / "Both" (default)
Set low Bi-level light output	5% up to 50%, equals 0.5 - 5.0 V for the 0-10 V control
Set high Bi-level light output	50% up to 100% (equals 5.0-10.0V for the 0-10V control)
Set Bi-level motion timer	2 minutes +
Set OFF motion timer	60 min default – can be turned OFF
Bluetooth inactivity timeout	5 min default

18 Minimum requirements: Bluetooth 4.0, iOS 7.1+.

Daylight sensor	Defaults to Disabled
Broadcast detection	“DOT” functionality– defaults to disabled
Test Mode	Defaults to Disabled

Controls

For the demonstration, the project team utilized the sensor in stand-alone and networked modes by dividing the site into two sections. The stand-alone version achieved via a dedicated control power pack was installed on 14 poles west of the overpass (see). The 12 poles east of the overpass were paired with the networked control solution. Each existing fixture was equipped with one wireless RF control lighting module (also called node) and one sensor as shown in Figure 10.

Figure 10: Existing streetlight (left), demonstrated communication node (right).

Source: Cree, Lumewave

The demonstrated control system networks enabled luminaires to create a wireless mesh network lighting system. The control system adjusts light levels based on sensor inputs, user defined schedules and sensitivity settings. Enabled LED lights can be dimmed to any level in five percent steps in addition to OFF. Controls can be based on a multi-step time schedule, occupancy events, networked events from nearby poles, photocell control, and astronomical time.

Technology Installation

The sensors and power packs were procured directly from the manufacturer to augment the networked control system. At the time of procurement, the sensor production was a third generation prototype. Material costs are provided in Appendix D. After final production, it is expected that procurement of the system will occur in the traditional distribution chain used by the lighting industry. This includes manufacturer representatives, electrical distributors, contractors and the end-user.

The lighting system ownership belongs to City of Davis. Maintenance duties are performed by the City. An overview of the lighting system, including a troubleshooting guide, was provided to the City at the completion of the project.

Contractor Selection

Installation team qualifications were based on their experience working with outdoor lighting systems. Contractors with knowledge of outdoor lighting code and previous experience in the outdoor sector were prioritized. A request for quote was sent electronically to three contractors for quotation. The project was awarded to the low bid contractor.

System Installation

The project team provided a traffic control plan (TCP) as required by the by the local police department and city. The City Works department and Police Dispatch were informed in advance about the planned day of installation. An installation guide including industry best practices was provided to the contractor, which provided necessary detail for both stand-alone and networked system installation. The guide is provided in Appendix E. Installation site photos are provided in Figure 11 and Figure 12.

The installation team consisted of six contractor employees and one project staff member. Four of the team members were dedicated to support the traffic control equipment (cones, towable illuminated traffic signage, hand held signs to indicate drivers to slow down, etc.), while two dedicated crew members were part of the boom truck and retrofitting team. The project staff member supported the installation crew with hardware assembly, wiring and troubleshooting.

Figure 11. Installation Preparation

Source: CLTC

Figure 12. East Section Installation with Traffic Control Plan

Source: CLTC

The occupancy sensor was mounted on the bottom of each fixture door and carefully oriented so the sensor arrays are perpendicular to the roadway and detection direction. A fully assembled luminaire is shown in Figure 13.

Figure 13. Installed Stand-Alone Configuration

Sensor (bottom), Photocell (top)

Source: CLTC

System Commissioning

For this demonstration, the majority of sensor and RF-system settings were set to match the settings of the "stand-alone" demonstration area. This was done to gather comparable data between the two demonstrated systems. One major exception is the "Set Bi-level motion timer" setting. The stand-alone power pack version has as a minimum setting of 2 minutes while the networked system has the capability to be controlled with a minimum of 1 minute timeout. The project team elected to evaluate at the shortest timeout available for each configuration to compare energy savings associated with this setting.

Sensor settings for both stand-alone and networked systems were configured to the settings shown in Table 3. In addition, to accurately compare the performance of each enabled/demonstration luminaire, the time clock, scheduling, tuning and trimming settings of the sensor's photocell for both stand-alone and networked systems were configured with the same settings:

- Turn fixtures ON 0.5 hour before sunset; dimming level set to 10.0 Volt, or 100% load
- At the local astronomical sunset the fixtures are dimmed to 2.0 Volt (~20% load)
- Ramp fixtures to 10.0 Volt, or 100% load, when motion is detected
- Time out back to ~20% load after no sensed occupancy
- Turn fixtures OFF 0.5 hour after sunrise the fixtures; using relay feature

Table 3. Demonstration Sensor Setting Configuration

Control Feature	Setting Options
Sensitivity for direction A	High Gain
Sensitivity for direction B	High Gain
Motion output filter	Both, slow and fast moving objects
Set low Bi-level light output	20%, or 2.0 V
Set high Bi-level light output	100%, or 10.0 V
Set Bi-level motion timer	2 minute for stand-alone/1 minute for networked
Set OFF motion timer	Function not used
Bluetooth inactivity timeout	5 minutes
Daylight sensor	Disabled
Broadcast detection	Disabled
Test Mode	Disabled

After the installation of the lighting system, additional commissioning and troubleshooting activities were performed to achieve full functionality of the system at the demonstration site:

- One pole was commissioned to perform at 80 percent light output during periods of occupancy to evaluate additional savings of this control strategy.
- Three luminaires had no adaptive control capabilities, with the luminaires operating in HIGH mode (100 percent ON) overnight use, but OFF over the day. One typical wiring issue that leads to this behavior is the shortening the 0-10V control wires on installation. This was confirmed and re-wired by the Contractor during a follow-up site visit.
- Four luminaires had no adaptive control and with the luminaries operating in LOW mode (20 percent ON) overnight use, but OFF over the day. This was not attributed to installation error. The TOP900 nodes were exchanged for functional spare units. The faulty units were provided to the manufacturer for additional troubleshooting. At the time of the report, the outcome of this troubleshooting is unknown.
- One luminaire operated at 40 Watts during the day and OFF at night, with no control to higher or lower state. This was not attributed to installation error. This unit was replaced with a new TOP900 node by the Contractor during a follow-up visit.

Multiple luminaires in the stand-alone section of the demonstration turned off after a 60 minute timeout, as opposed to dimming to a low level as commissioned to behave. Most of the luminaires behaving as described were on poles surrounded by heavy foliage from nearby trees. To address this issue, the manufacturer updated a setting in the power pack controls to default the luminaire to ON instead of OFF during the night schedule. Units were physically exchanged with an updated power pack unit per affected pole/luminaire during a follow-up site visit by the Contractor.

Chapter 5: System Characterization

Staff completed a series of tests to fully characterize the baseline and post-retrofit lighting systems. Work included preliminary control system characterization, as well as in-situ testing prior to technology installation at the demonstration site. Post-retrofit testing occurred over a period of several months.

Controls Systems

At the time of this report, no dedicated test procedures were identified for the evaluation of microwave-based occupancy sensors in outdoor applications. Compared to other occupancy sensor technology types, microwave-based sensors are more sensitive to central motion (to-and-from the sensor) than to lateral motion (across zones). This requires a unique test procedure for microwave-based occupancy sensors. The project team developed sensor testing procedures, based on NEMA-WD7 and other roadway related sensor guides[19] to confirm manufacturer performance claims of long range sensing functionality and reliability of the MWX sensor family.

Occupancy sensor coverage was determined by the sensors detection method, the physical orientation and placement in space, the field of view, detection range(s) and lens if applicable. The coverage pattern provided by the manufacturer communicates its detection range and coverage area for a specific application height and orientation. Unless otherwise stated, the manufacturer claimed coverage is based on the sensor's maximum sensitivity setting under ideal situations.

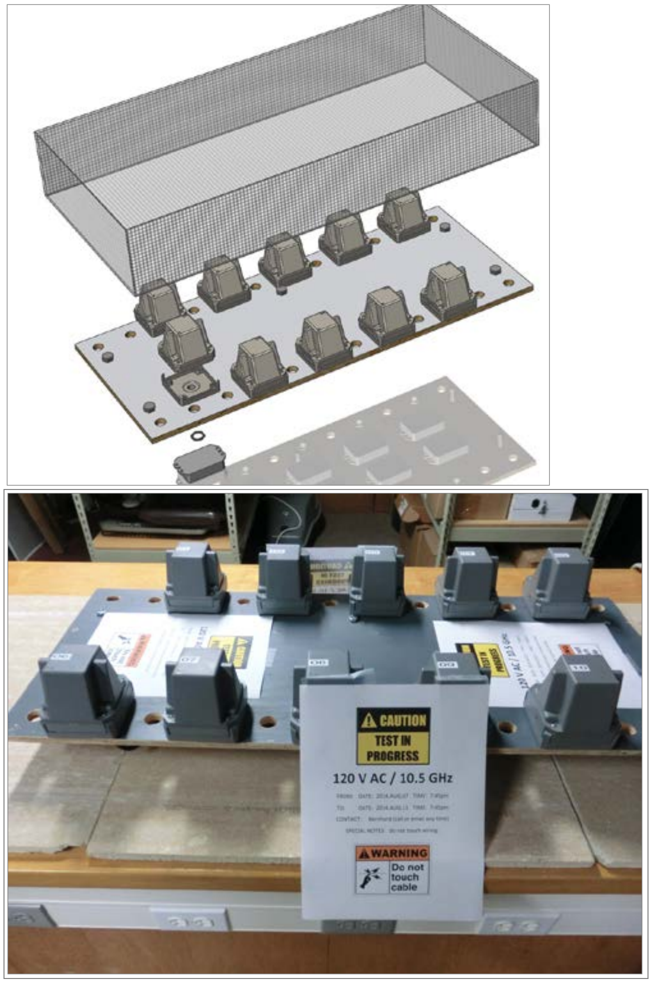
Reliability

The selected sensing solution for the demonstration is a prototype product. Operating the sensors for a defined period of time, or a "burn-in", is an industry standard recommendation for new products for the purposes of induce thermal and electrical stress to provoke failure. Microelectronic devices with inherent defects leading to product failure can often be identified during the burn-in period. The burn-in period minimizes infant mortality of electronic devices deployed at the demonstration site.

Sensors were mounted in a test rack and subjected to a burn-in period of 240 hours, shown in Figure 14. Each sensor has a distinct identification 32-digit code which was collected during the burn-in period to support troubleshooting efforts. No failures occurred during the burn-in period.

19 MSSLC-"Model Specification for Adaptive Control and Remote Monitoring of LED Roadway Luminaires"

Figure 14. Burn-In Process to Avoid Premature Sensor Failure

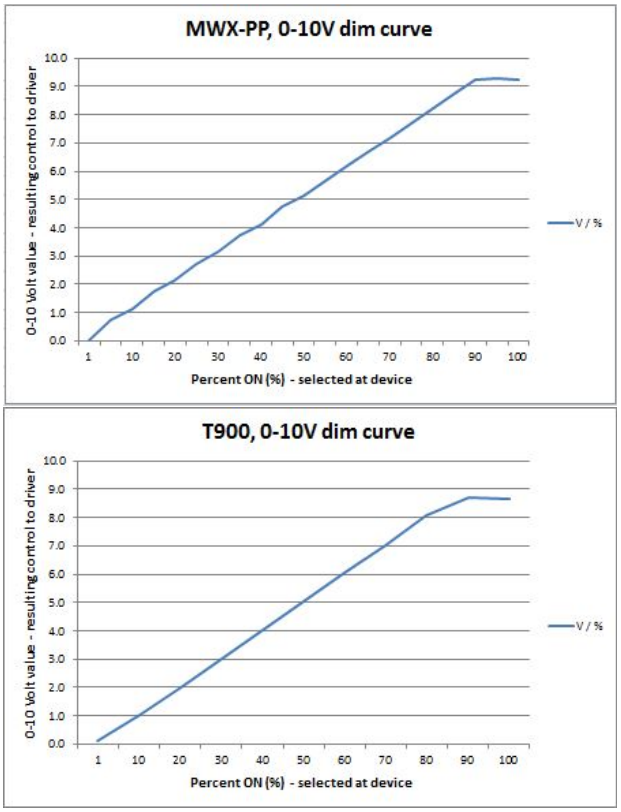


Source: CLTC

To characterize the dimming curve correlating the control signal to light output for stand-alone and networked systems, data was collected using laboratory grade equipment in a controlled, laboratory environment. A dimming curve maps control signals to target light output and corresponding power of the fixture. Data was gathered at a resolution that provides adequate granularity for accurately commissioning the system after installation at the demonstration site. The project team identified five percent light output increments as appropriate for the stand-alone system, which corresponds to the highest resolution offered by the software. Ten percent light output steps were identified for the networked system, with one percent steps being the highest resolution offered by the software.

Both stand-alone and networked lighting system dimming curves show a linear progression from 1 percent to 90 percent control value, with a plateau from 90 percent to 100 percent control setting, as shown in Figure 15. This means dimming changes between 90 and 100 percent do not produce a change in light output.

Figure 15. Dimming Curves for Stand-Alone (Left) and Networked (Right) Systems



Source: CLTC

Preliminary Sensor Performance

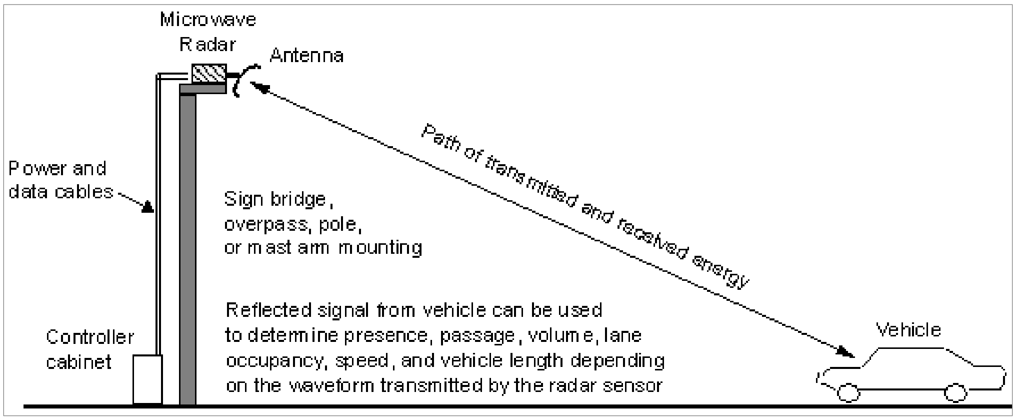
A preliminary evaluation was conducted on the 26 microwave sensors selected for use in the demonstration to confirm the function of several sensor characteristics.

- Bluetooth commissioning smartphone application
- Three different detection ranges (low, medium and high gain setting)
- Actual detection of occupants such as pedestrians and motorized vehicles in a test scenario.

The project team referenced the US Department of Transportation *Freeway Management & Operations Handbook*, Section 15.2.6.3 *Microwave Radar* best practice detection methodology when defining the test procedure as shown in Figure 16. [20] Figure 17 provides typical parameters encountered when working with microwave radar technology in occupancy controlled environments, such as angle of incident and related range. The test bed used to evaluate the microwave sensor is shown in Figure 18.

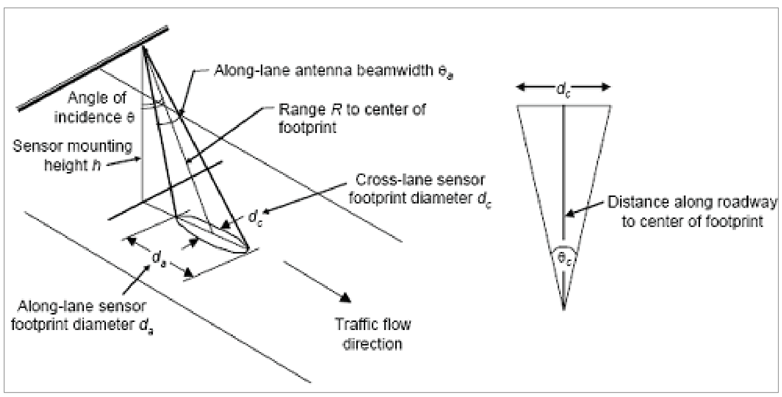
20 US.DOT "Freeway Management & Operations Handbook", FHWA-OP-04-003 (Sept.2003), Section 15.2.6.3 "Microwave Radar"; http://ops.fhwa.dot.gov/freewaymgmt/publications/frwy_mgmt_handbook/chapter15_01.htm

Figure 16: Microwave Radar Recommended Test Setup



Source: U.S. Department of Transportation, "Freeway Management & Operations Handbook"

Figure 17: Microwave Radar Test Bed Parameters



Source: U.S. DOT, Publication# **FHWA-HRT-06-139, Figure 5-64**[21]

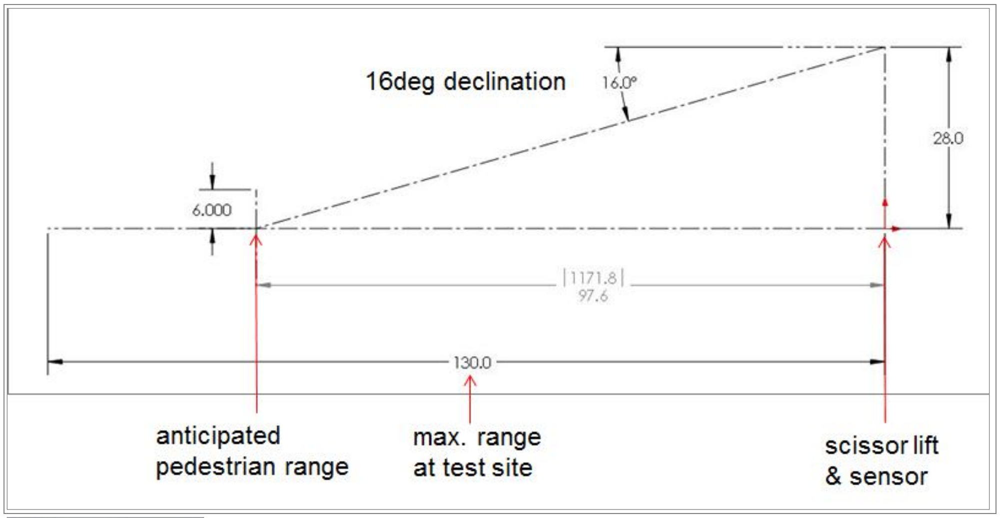
Figure 18: Sensor Performance Test Bed – Top View

21 http://www.fhwa.dot.gov/publications/research/operations/its/06139/chapt5d.cfm

Source: CLTC

A scissor lift was used to provide a sensor mounting height of 28 feet above grade to simulate the demonstration site pole height. The sensor was mounted such that the active sensor array faces down the test area. The secondary sensor array facing the east was deactivated via the Bluetooth commissioning smartphone application. The angle of incidence for the mounting location of the sensor was 74 degrees.

Figure 19: Sensor Test Site Dimensions



Source: CLTC

Preliminary performance testing of the microwave occupancy sensor was conducted with a pedestrian occupant (2 mph) and a two-door automobile occupant (15 mph) each passing through the test bed. Six of the 27 sensors were tested with both sensing arrays "A" and "B", for detection range settings at "HIGH" and "LOW" gain. All 27 sensors were tested on sensing arrays "A" and "B" for detection range setting "MED" gain. Figure 20 and Figure 21 provide the detection ranges observed during this preliminary test. The results were collected and plotted, shown in Figure 22.

Figure 20. Sensor Performance Testing Parameters with Pedestrian

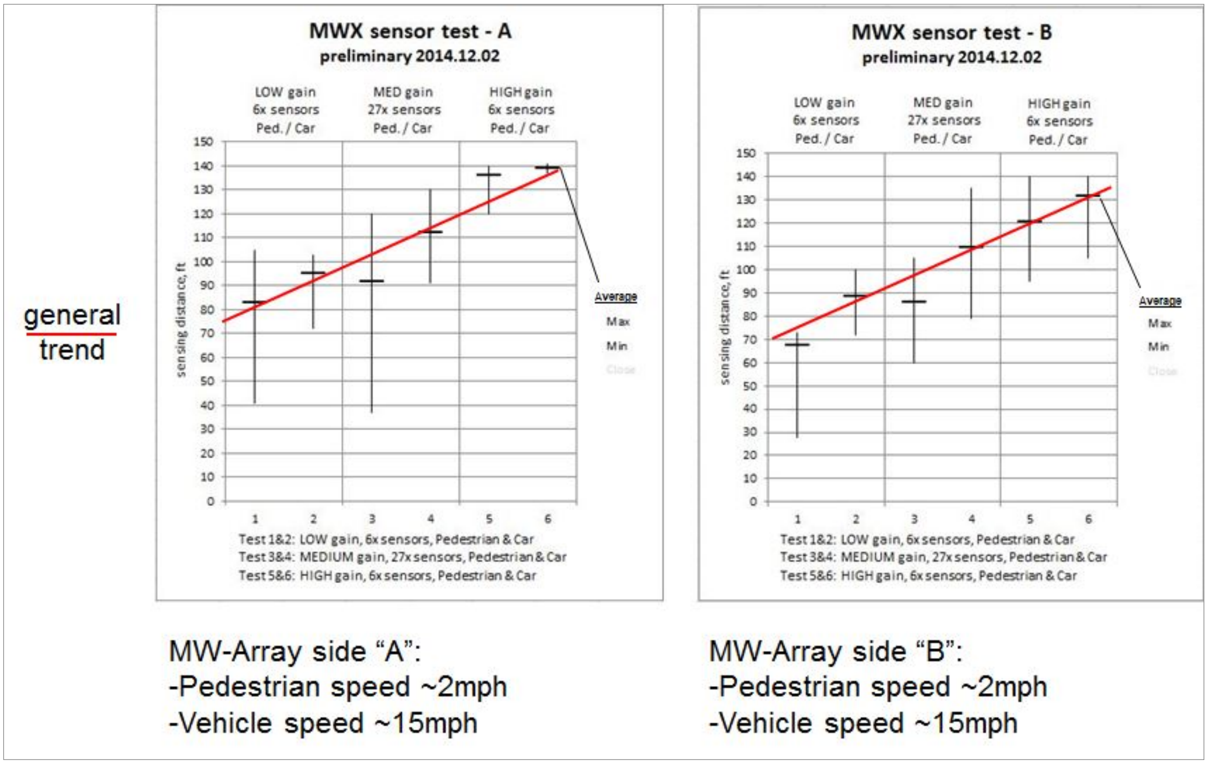
Source: CLTC

Figure 21. Sensor Performance Testing Parameters with Two-door Automobile

Source: CLTC

All sensors tested detected and logged 100 percent of occupants in the test bed, with no missed or false triggers. Two sensors had one of the two arrays not function; both sensors were replaced with new units prior to deployment in the demonstration site. The test bed for the preliminary testing has a maximum range of 140 feet. This corresponds to the observed sensor detection for the "HIGH" gain setting.

Figure 22. Microwave Sensor Preliminary Testing Results



Source: CLTC

In-Situ Sensor Performance

To determine the usability of the sensor for longer distances and higher occupant velocities, additional sensor performance evaluations were conducted at a second, larger test area, shown in Figure 24. The site was selected for its maximum length of 300 feet. The test bed was prepared with side marker signs mounted to stands to indicate 25, 50, 75, 100, 150, 200, 250 and 300 feet distance from the sensor. Figure 23Figure 17 provides an example of the test bed setup.

Figure 23. Distance Markers at Test Bed

Source: CLTC

Figure 24: UC Davis Waste Water Treatment Plant

Source: CLTC

A boom truck was rented for the test day and positioned on-site next to one of the circular water treatment basins, as marked via "X" in Figure 24, and the platform raised to 28 feet above grade. For testing, the sensor was wired to a spare fixture door of the demonstration site fixture type connected to a node. The door assembly was attached to the bottom of the boom truck platform, powered by an extension cord to 120 VAC, and the sensor oriented to be level to the ground and as intended for normal installation directed towards the expected traffic flow.

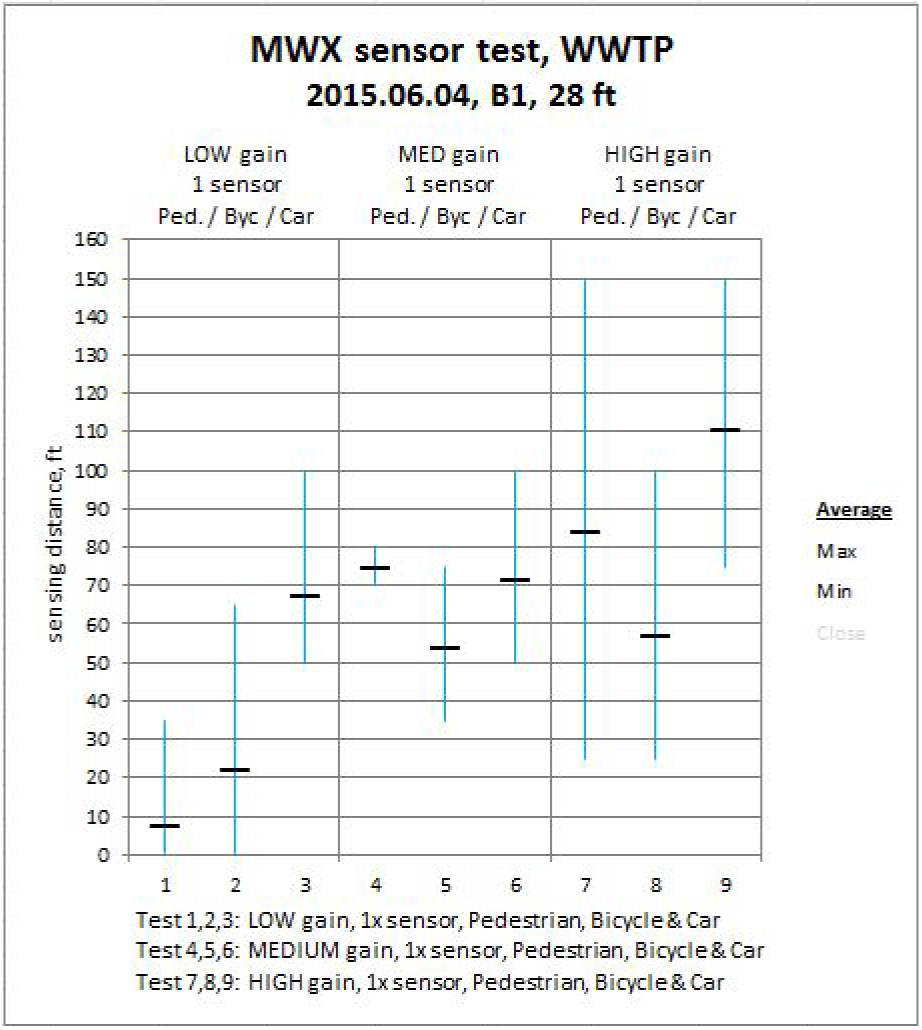
The control-system software includes a test option that provides a visual confirmation of triggering and logging events. This feature was used during the in-situ testing to record the sensor trigger event and correlate it to the occupants' distance from sensor indicated by the prepared side marker signs and the occupants speed. Occupant types included in the testing are to include pedestrian, bicycle and cars. For more accurate detection range characterization, sensor performance testing was conducted on one sample of the bi-directional microwave occupancy sensor.

Figure 25. Fixture Door with Sensor and Node, 28 feet above Grade

Source: CLTC

Sensor testing was conducted with varying occupant speeds (Pedestrian from 2 mph up to 10 mph; Bicycle from 5 mph to 24 mph; and Car from 5 mph to 45 mph) to confirm reliable sensing function at higher speeds. Testing was conducted during a hot day, to demonstrate an improvement over conventional PIR technology, which is limited by hot conditions. The sensor captured all occupants and vehicles. For slow moving occupants and vehicles, the sensor, whet set at low gain, detected objects at approximately 10 feet and 70 feet, respectively. When the sensitivity was increased to high, the sensor's detection ranged improved to approximately 60 feet and 110 feet for pedestrians and cars, respectively.

Figure 26: In-Situ Sensor Test Results



Source: CLTC

System Energy Use

To calculate lighting energy saved by each demonstration system configuration, Equation 1 was used where lighting energy saved is equal to the post retrofit energy consumption subtracted from the baseline energy consumption (adjusted to post-retrofit operating schedules).

Equation 1: Net Energy Savings

$$NES = BEUa - PEU$$

- NES = Net energy savings
- BEUa = Baseline energy use (adjusted)
- PEU = Post-retrofit energy use

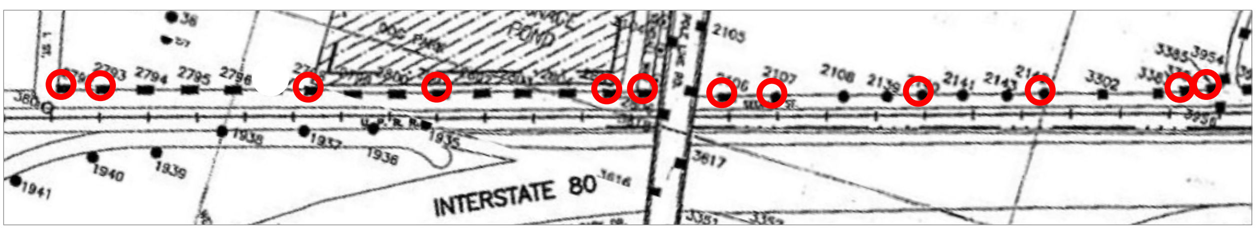
When comparing system energy use, the project team identified the following system configurations and associated data collection method as appropriate for inclusion:

- LED Baseline System, photocell control (*One-time Power Measurement; Estimated Energy Use*)
- LED System, photocell and occupancy stand-alone sensor control (*Continuous Monitoring*)
- LED System, photocell and occupancy networked sensor control (*Continuous Monitoring*)
- LED System, photocell and occupancy networked sensor control with high-end trim (*Continuous Monitoring*)

The demonstrated technologies are variable loads with variable use. One-time laboratory grade power measurements were taken of the LED baseline system at 100 percent output. Continuous energy measurements were taken for a 61 day post-retrofit period. Data was extrapolated to calculate the annual energy consumption of the system. The uncertainty of the collected data was quantified by reviewing sources of error such as modeling, sampling, measurement equipment or human error in handling the equipment. The maximum allowable uncertainty level was 50 percent of annual reported savings at 68 percent confidence.[22]

To compare the stand-alone and networked configuration, six poles of each configuration were monitored, shown in Figure 27.

Figure 27: Poles Monitored for Energy Use



Source: City of Davis

Data Collection Equipment

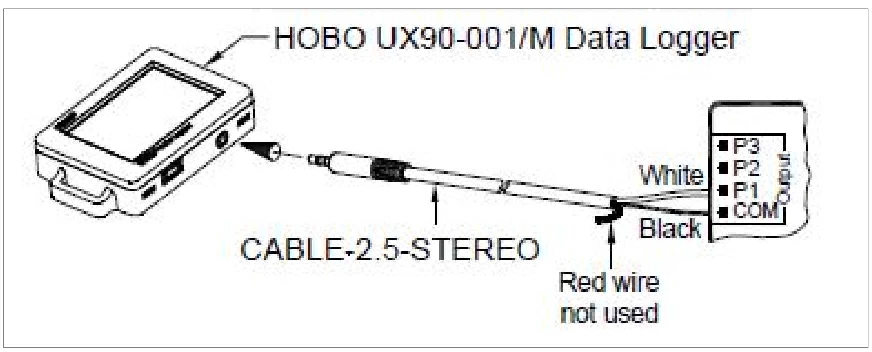
To gather the continuous energy measurements of the post-retrofit system, revenue grade monitoring systems were deployed at each of the 12 poles shown in Figure 24. The monitoring system consists of three components: current transformer (CT), meter and data logger shown in Figure 25. The pulse logger was connected to the WattNode through the 2.5 mm stereo connector wire, shown in Figure 29. A summary of the monitoring system equipment specifications is provided below with full specifications provided in Appendix B.

22 ASHRAE 14-2002, Section 6.2

Figure 28. Energy Use Monitoring System

Source: CLTC

Figure 29. Monitoring Equipment to WattNode Wiring Configuration, Zoom



Source: CCS

Current Transformer

The Continental Control Systems (CCS) revenue grade 20-amp Accu-CT® line of split-core high-accuracy current transformer (CCS-ACT-0750-020) was deployed for this demonstration. The CT has an accuracy rating that exceeds IEEE C57.13 class 0.6 and IEC 60044-1 class 0.5[23].

At the time of this demonstration, the high accuracy CT was only available in the 20-amp sizing, which is oversized for the load being monitored. The expected maximum

23 http://www.ccontrolsys.com/w/CT_Accuracy_Standards

load per pole mounted luminaire is 100 Watts at 100 percent ON setting and 20 Watts at 20 percent dimmed setting.

To increase the current transformers pulse count, each deployed CT was deployed with eight loops of loadbearing cable run through the detection center of the CT, see Figure 28. Additional loops provide higher resolution data collection when using oversized CTs. Loop scaling factors are included in the energy consumption calculations.

Revenue Grade Meter

The CCS RWNC-3Y-208-MB *WattNode Revenue* meter selected for use in the demonstration meets the accuracy requirements for ANSI C12.1-2008 and C12.20 Class 0.5. ANSI C12.1 is the performance standard for electricity revenue meters. ANSI C12.20 specifies the metering performance and influence limits for 0.2 percent and 0.5 percent accuracy meters. ANSI C12.1 and C12.20 standards require the use of CTs that meet IEEE 57.13 accuracy requirements, such as the Accu-CT® line of split-core high-accuracy CT described in the section above.

Revenue grade WNC WattNode meters have dedicated certification of calibration valid for 8 years of use until recalibration is recommended. Calibration certificates are available upon request.

Data Logger

The Onset Hobo UX90-001M pulse logger specified for use in the demonstration has an extended memory of 512 KB that can hold up to 346,795 measurements with a change of state frequency of up to once every second. HOBOware software was used to configure the logger with user specified settings. The logging interval of the data logger was chosen to be equal or smaller than the minimum timeout interval of the occupancy sensor, or one minute.

The HOBOware software was used to download the logged data. The outputs of the software program provide change-of-state timestamps and the corresponding pulse count recorded for the defined time interval.

Equipment Installation

Logging equipment was installed by CLTC staff per the wiring diagram and settings provided in the *M&V Plan* section of this report. Installation took place on January 15th and 16th, 2015 at each pole selected for monitoring. Tools and safety equipment per OSHA requirements and UCD Personal Protection Equipment (PPE) policies were used during the installation.

Monitoring equipment was installed at bottom of pole at the hand hole access point, shown in Figure 39. Troubleshooting was performed as each pole was installed, confirming functionality of monitoring system at the time of installation. Short-term energy logs were collected the day of installation to compare to one-time power measurement (OTM) to confirm that the logging equipment functioned as intended.

The monitoring equipment was deployed in a sealed plastic bag to provide additional protection from outdoor weather conditions. Intermittent data collection was retrieved on January 22, 2015; the final data collection took place on March 17, 2015.

Baseline Systems

To benchmark the energy performance of the pre-retrofit LED lighting system with photocell control, a one-time power measurement at full output was conducted at the base of the pole. A system wattage of 92.0 Watts was recorded. The average day length in Davis shifts from 10.5 hours in July to 14.5 hours in December. Based on the average day length and typical photocell settings previously described, the estimated annual energy use of the LED baseline system at the demonstration site is 10,818.6 kWh.

Demonstration Systems

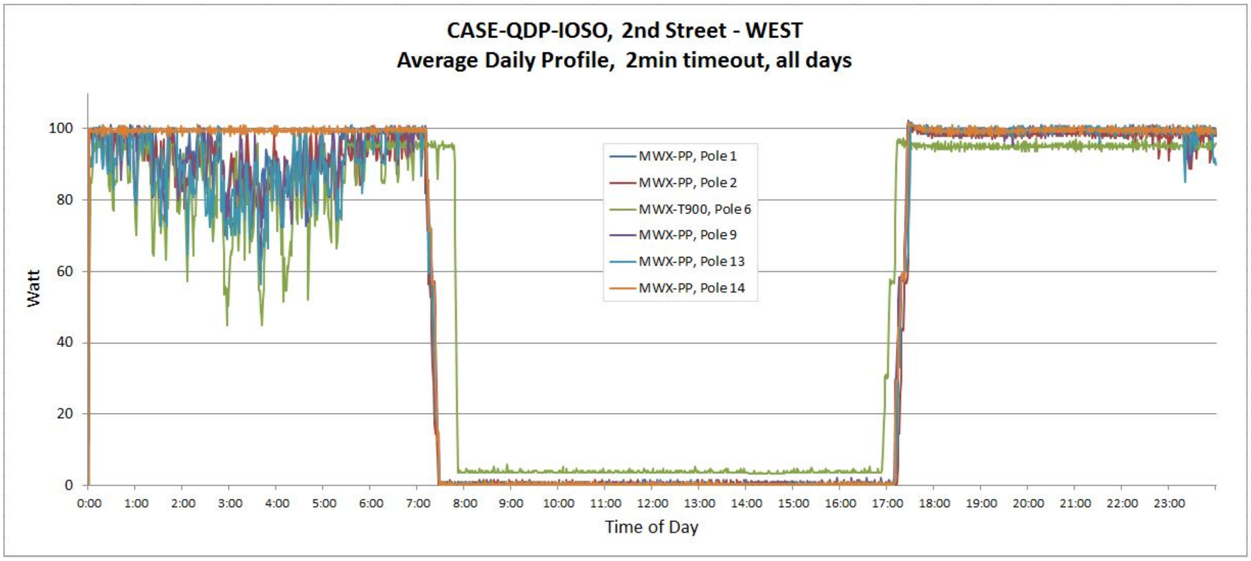
To quantify the energy performance of the post-retrofit lighting system configurations to the baseline system, lighting energy use data was collected from January 16, 2015 to March 17, 2015. A summary of the energy analysis is provided in Table 5. Issues identified during energy analysis resulting in exclusion from final results are noted per system configuration: stand-alone (PP) and networked (TOP900). Profiles focused on during energy analysis are bolded.

Table 5: Post-Retrofit Monitoring Summary

Pole ID	Power Pack (PP) or TOP900	Monitoring Notes
C2792-01	PP	LOW trim at 40%
C2793-02	PP	LOW trim at 40%
C2798-06	TOP900	TOP900 Model in the West Section
C2801-09	PP	Atypical Profile
C2805-13	**PP**	**Selected as Representative Profile (Stand-Alone)**
C2806-14	PP	Log results unexpected (80% max)
C2106-15	TOP900	Stuck in LOW mode (at 20%)
C2107-16	TOP900	Stuck in LOW mode (at 20%)
C2140-19	**TOP900**	**Selected as Representative Profile (Networked)**
C2142-22	TOP900	Stuck in HIGH mode (at 100%)
C3384-25	**TOP900**	**HIGH trim at 80%.**
C3385-26	TOP900	Stuck in HIGH mode (at 100%)

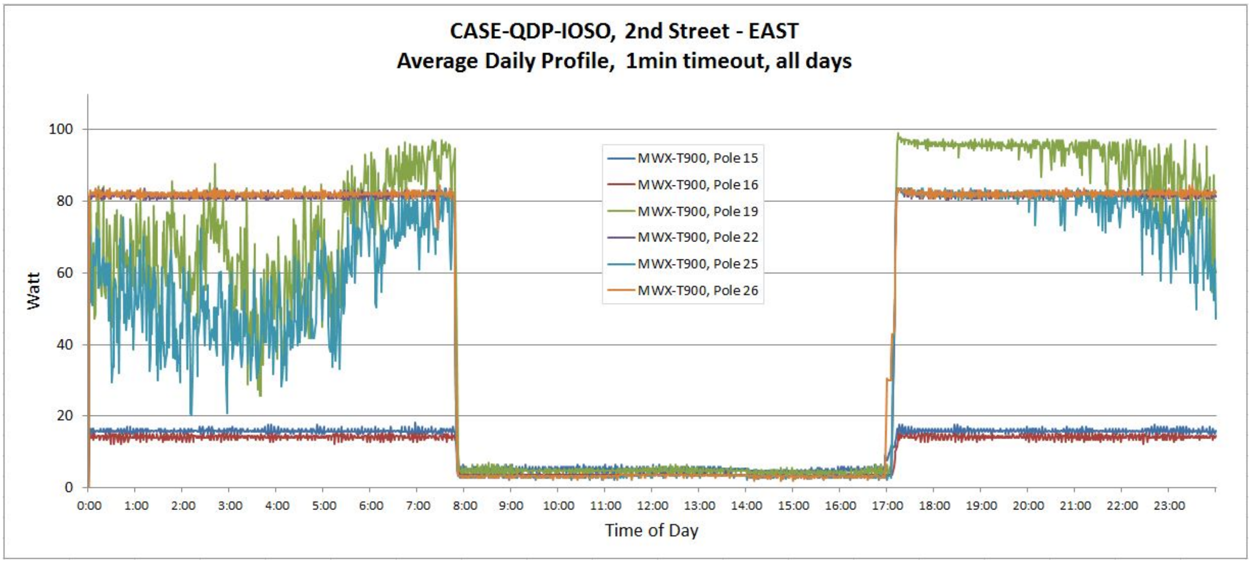
Figure 30 and Figure 31 provide average daily profiles for the poles in the Stand-Alone and Networked systems respectively.

Figure 30. Average Daily Profile for Stand-Alone System Poles



Source: CLTC

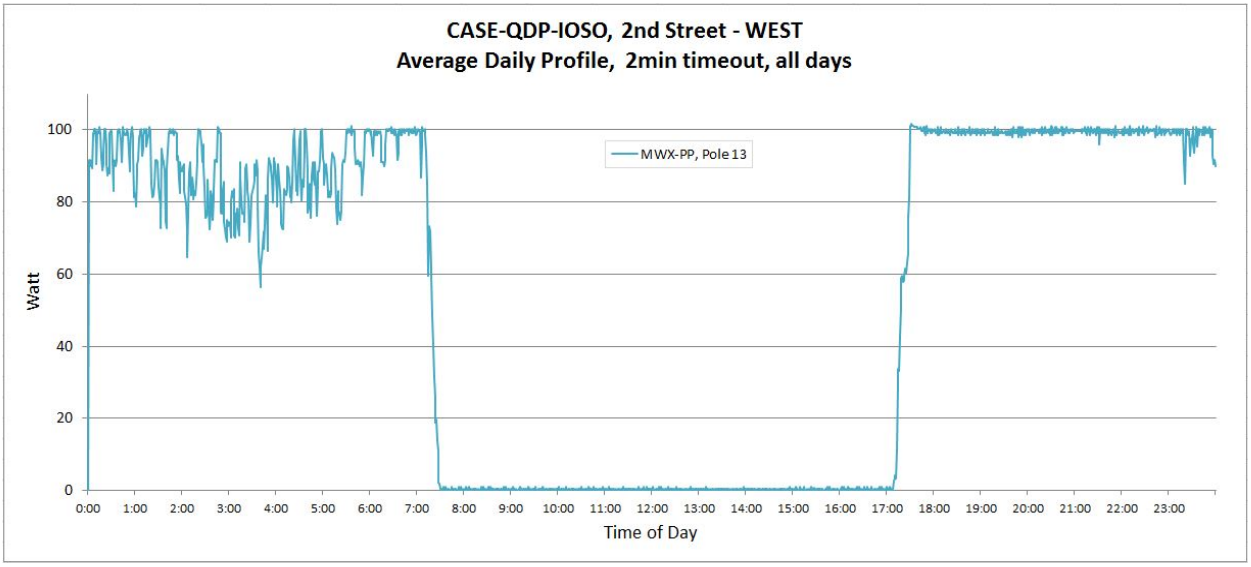
Figure 31. Average Daily Profile for Networked System Poles



Source: CLTC

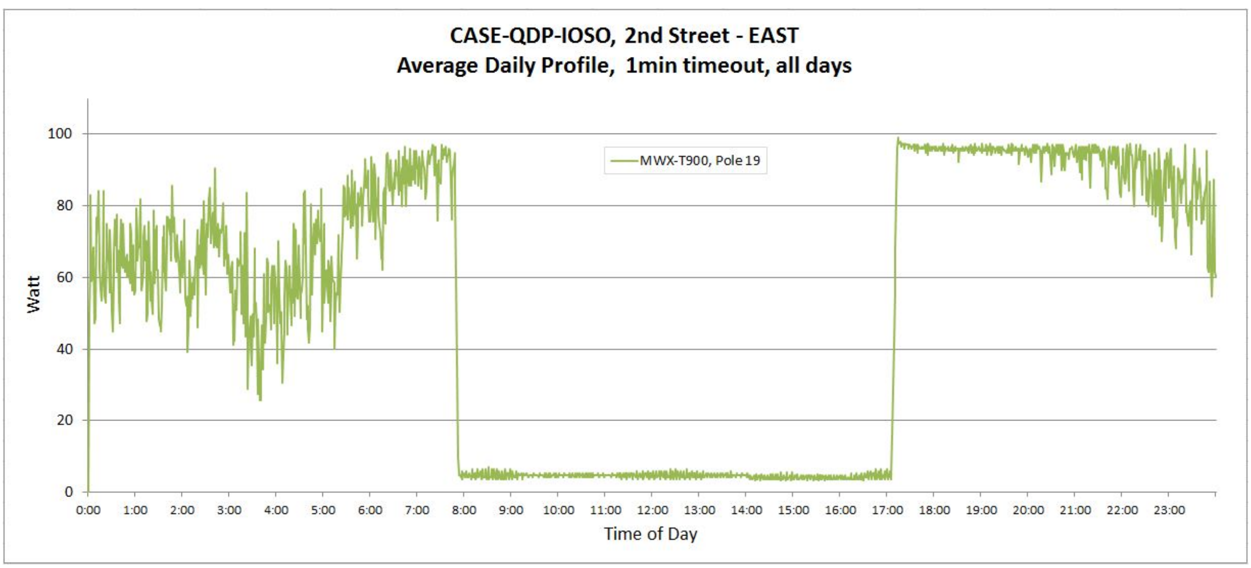
Energy use logs for poles identified as representative of stand-alone (Pole 13) and networked (Pole 19) system behaviors are provided Figure 32 and Figure 33 respectively.

Figure 32. Average Daily Profile of Representative Stand-Alone Pole



Source: CLTC

Figure 33. Average Daily Profile of Representative Networked Pole

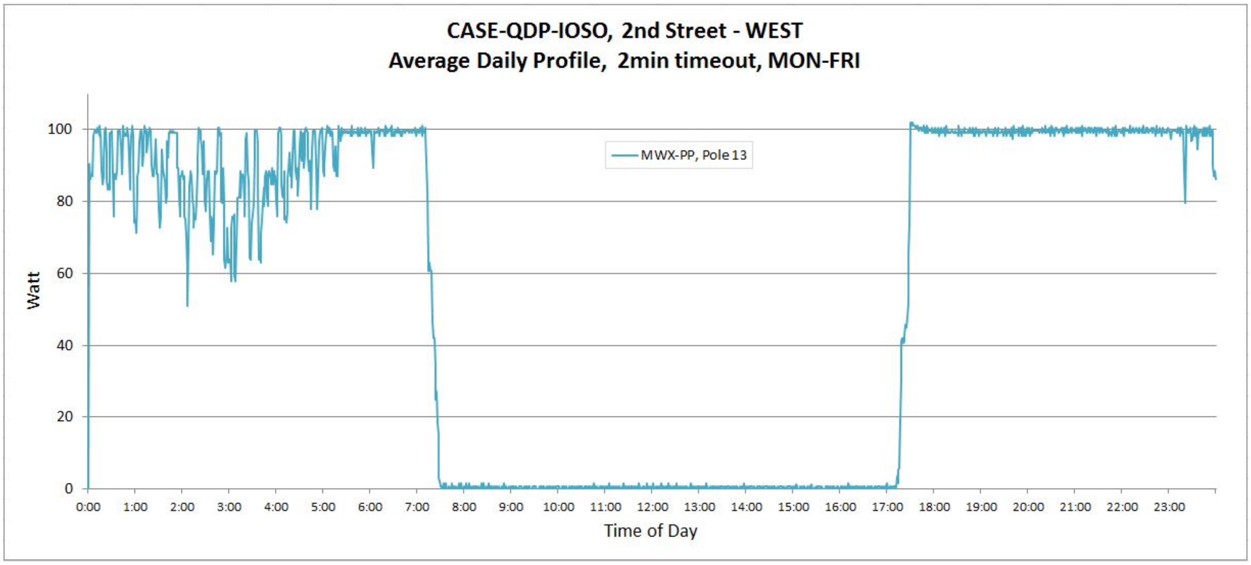


Source: CLTC

The difference in average energy use over 60 days between the stand-alone and networked systems is most noticeable in the timeframe from 10:00 pm until the sunrise.

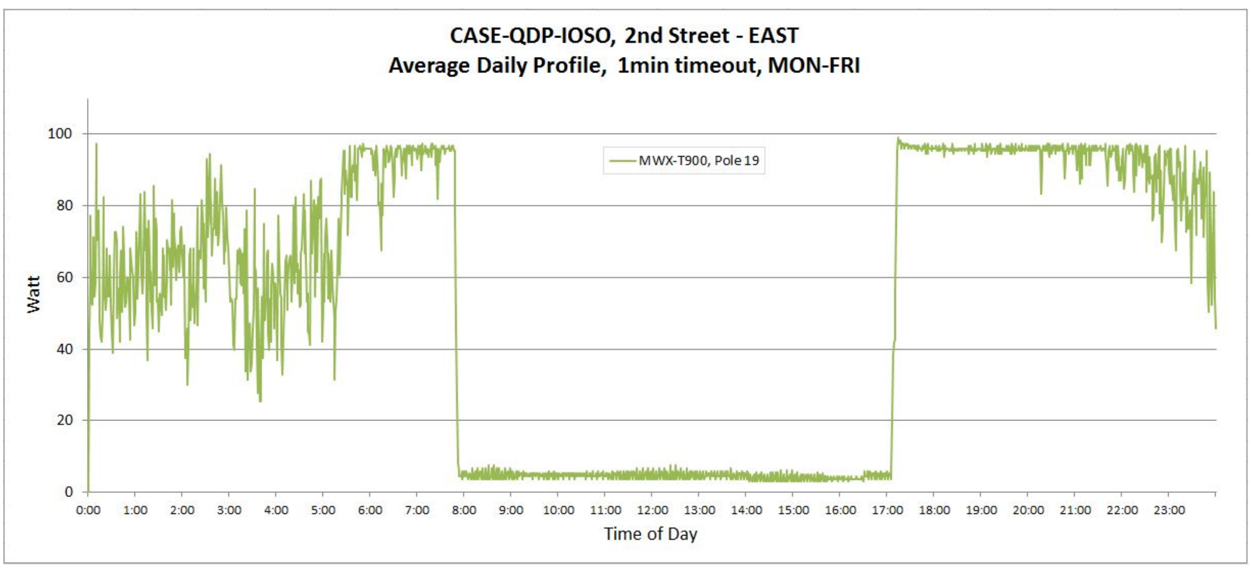
Analysis also focused on weekday use only, with average daily profiles for representative poles of each system provided in Figure 44 and Figure 45. The stand-alone pole (Figure 44) using a two-minute timeout has less energy savings than the networked pole (Figure 45) using a one-minute timeout.

Figure 34. Average Daily Profile of Representative Stand-Alone Pole – Weekdays



Source: CLTC

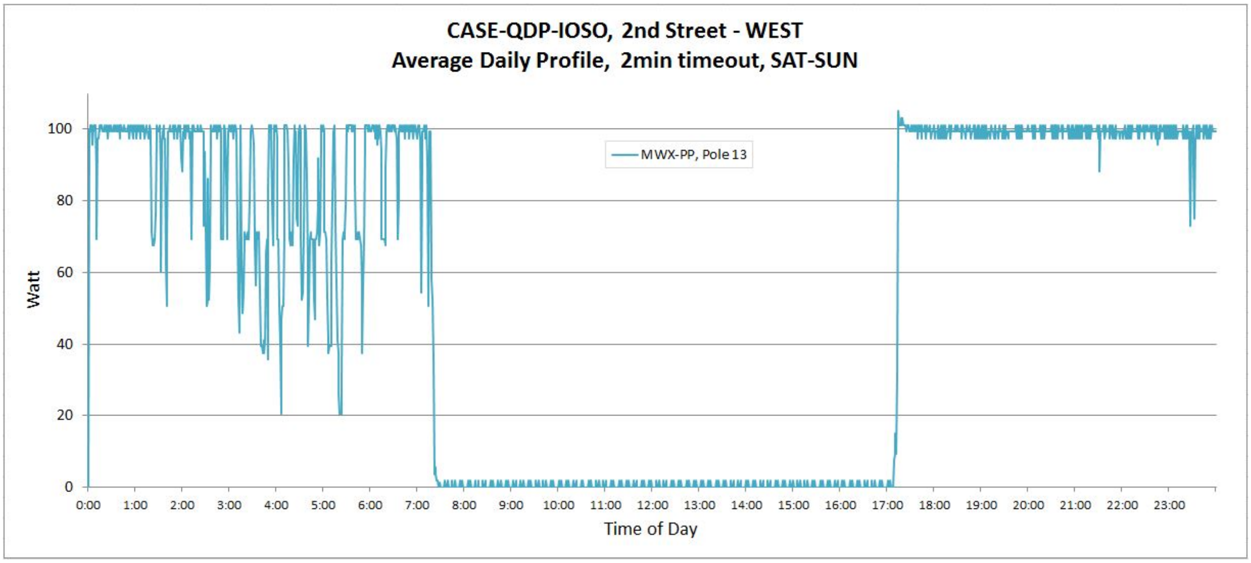
Figure 35. Average Daily Profile of Representative Networked Pole – Weekdays



Source: CLTC

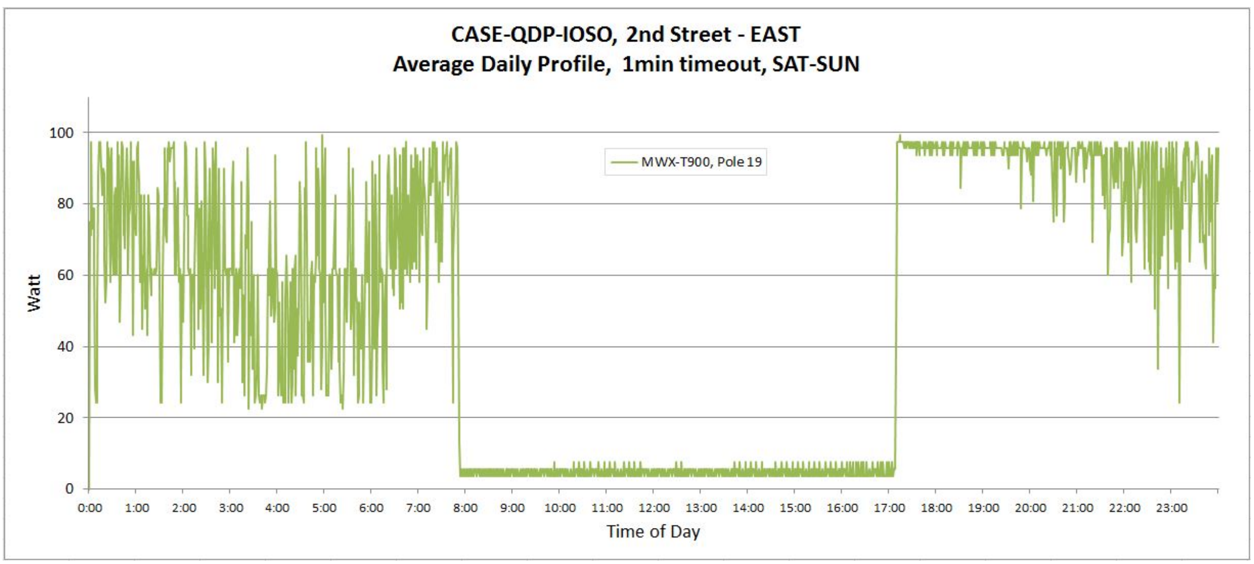
Weekend only use, and average daily profiles for representative poles of each system configuration provided in Figure 46 and Figure 47. Weekend average daily profiles show higher energy use than the average for the monitoring period. The stand-alone pole (Figure 46) using a two-minute timeout has less energy savings the networked pole (Figure 47) using a one minute timeout.

Figure 36. Average Daily Profile of Representative Stand-Alone Pole – Weekend



Source: CLTC

Figure 37. Average Daily Profile of Representative Networked Pole – Weekend

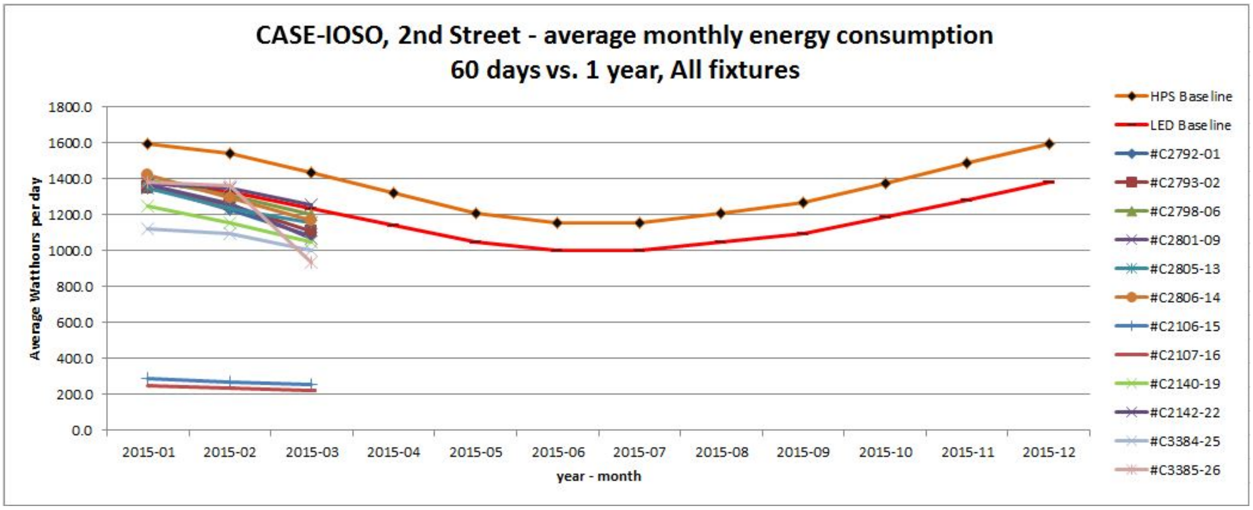


Source: CLTC

The average day length in Davis shifts from 10.5 hours in July to 14.5 hours in December. The baseline profile was calculated using system wattages at 100 percent light output when controlled by photocells with typical settings as previously described.

Data reduction was performed on collected energy logs to determine the average daily watt-hours consumed for each month monitored. Based on the monitoring period, two discrete values were calculated (January, February and March). The average monthly Watt-hours for the LED baseline without controls and logged energy use at the 12 poles are shown in Figure 48.

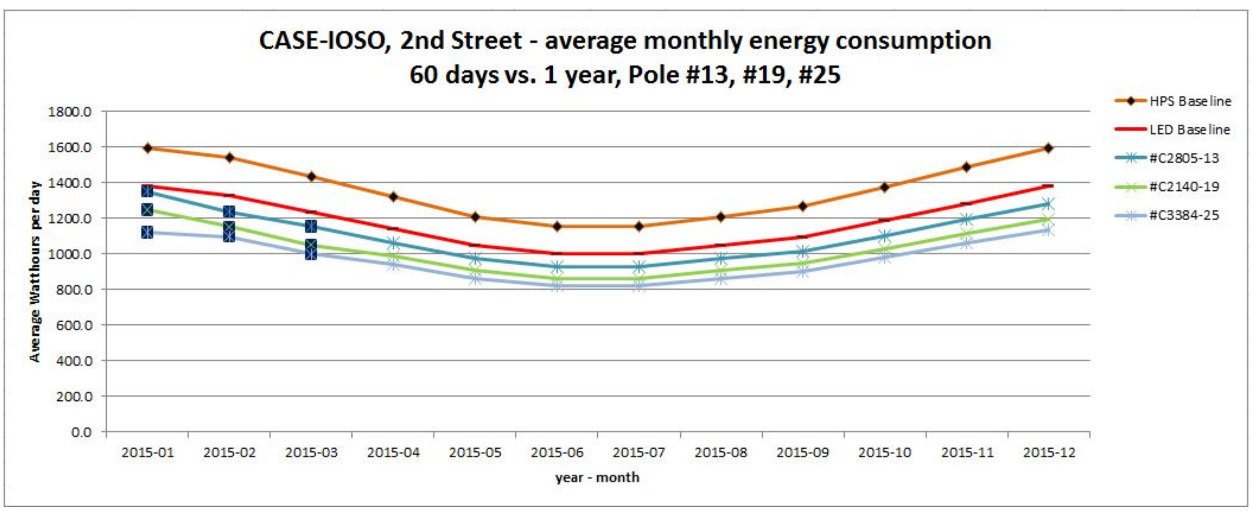
Figure 38. Average Daily Watt-hours per Month



Source: CLTC

Additional analysis was conducted on stand-alone system (Pole 13), networked system (Pole 19) and networked system with a high-end trim system (Pole 25). Using the known length of night per month, monitored data was extrapolated to calculate an annual energy use profile for each of the system configurations of interest, shown in Figure 39.. Occupancy rates collected during the monitoring period are assumed to be constant for the annual profile calculations.

Figure 39. Extrapolated Average Daily Watt-hours per Month



Source: CLTC

The energy use profiles of the three representative poles configurations were applied to the demonstration site to understand the expected energy consumption of the site for each configuration fully deployed. Calculated annual energy use for each control system configuration of interest is provided in Table 6.

Table 6: Annual Energy Use and Savings – Adaptive Controls

System	Annual Energy Use (kWh)	LED Baseline	Annual Energy Savings (kWh)	Percent Savings (%)
LED Baseline	10,818.6	100%	-	-
Stand-Alone (2-minute timeout)	10,488.5	96.9%	330.1	3.1%
Networked (1-minute timeout)	9,747.6	90.1%	1,071.0	9.9%
Networked with High-End Trim (1-minute timeout)	9,224.9	85.3%	1,593.7	14.7%

Source: CLTC

End User Survey Results

A post-retrofit site survey was deployed to evaluate the occupancy-based lighting system and the gather the importance of street lighting with respect to user preference and nighttime hazard detection for a cross-section of end user groups.[24] The complete survey document used during the evaluation is provided in Appendix C.

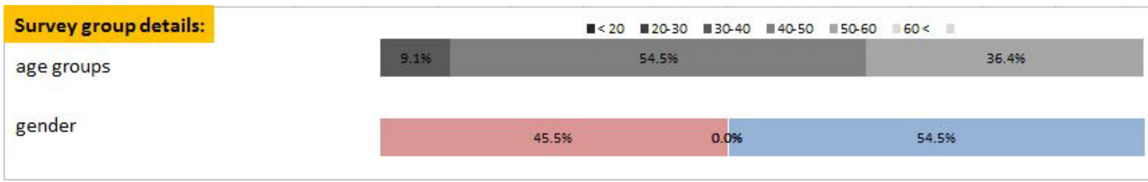
Invitations to attend the survey were sent to 46 individuals spanning the following user groups: lighting specialists, representatives, the manufacturer of the system hardware (Lumewave/Echelon), City of Davis, City of Woodland, City of Sacramento, City of West Sacramento, local businesses, the California Energy Commission project manager (CEC),

24 The site survey was designed to the guidelines of Basic Ethical Principles for Human Research (CITI-IRB) with voluntary participation

local utilities (SMUD, PGE) and the University of California Davis Facility Management team.

The end user survey took place on August 20, 2015, from 8 pm to 9:30 pm (PST). The local weather conditions were dry and approximately 85 degrees Fahrenheit with minimal wind. A total of 11 participants gathered at the demonstration site. The age of the survey participants range from 30 to 60 years. The gender was a mix of 45.5 percent female and 54.5 percent male. An age and gender breakdown of the survey participants is provided in Figure 40.

Figure 40. Survey Participant Age and Gender



Source: CLTC

Responses from the survey were collected from each participant. Survey responses were converted to a percentage of all answers given; where 11 answers equals 100 percent and one answer equals 9.1 percent. The questionnaire is separated in three main sections: General Street Lighting; Demonstration Site Street Lighting; Demonstration Site Adaptive Controls. For questions ranked on a scale, the reference values are defined in Figure 41.

Hand written notes were allowed as part of the survey. Two remarks noted the lighting to be "very uniform" and "much better than typical Davis Street Lighting". One recommendation noted the need for a "revisit the Second Street site after midnight to assess the function of the sensors at full dark and under more realistic conditions than the site survey visit timing permitted".

With respect to end user acceptance of the deployed technology, the demonstration of innovative occupancy sensors in the field provided a test bed to survey end users regarding their satisfaction with static street lighting and adaptive street lighting systems. 54.5 percent of the end users surveyed use the space as drivers of motorized vehicles and 18.2 percent walk.

Approximately 36 percent of end users reported dissatisfaction with general street lighting, while the same percentage reported satisfaction with general street lighting. The majority of respondents, 45.5 percent, 'feel safe' under general street lighting systems. The most distracting issue reported by survey respondents is shadowing/glare on objects in the street for general street lighting systems. Approximately 45 percent of respondents reported they are satisfied with the new lighting system for their task most frequently performed at the site. Forty-five percent of respondents reported they did not notice the adaptive control features of the demonstration site, that they were satisfied with the adaptive system and that they felt satisfied or highly satisfied with their feeling of safety while using the adaptive control system.

Figure 41. Scale Key

Key	Skip	strongly disagree		indifferent/abstention				strongly agree
grade	S	-3	-2	-1	0	1	2	3

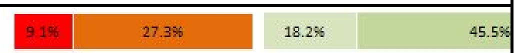
Source: CLTC

Table 4. General Street Lighting - End User Responses

1. Pick the task you do most frequently under general street lighting:		
Answer Options	Response Count	%
Drive motorized vehicle	6	54.5%
Bicycle	0	0.0%
Jog/Run	1	9.1%
Walk	2	18.2%
Other	1	9.1%
Skip	1	9.1%
2. How satisfied are you with general street lighting you have for that task at night?		
Answer Options	Response Count	%
Highly Dissatisfied	0	0.0%
Dissatisfied	0	0.0%
Slightly Dissatisfied	4	36.4%
Indifferent	2	18.2%
Slightly Satisfied	1	9.1%
Satisfied	4	36.4%
Highly Satisfied	0	0.0%
Skip	0	0.0%
Satisfaction with general street lighting for task	36.4% 18.2% 9.1% 3	
3. How safe do you feel with general street lighting you have for that task at night?		
Answer Options	Response Count	%
Highly Dissatisfied	1	9.1%
Dissatisfied	3	27.3%
Slightly Dissatisfied	0	0.0%
Indifferent	0	0.0%
Slightly Satisfied	2	18.2%

Satisfied	5	45.5%
Highly Satisfied	0	0.0%
Skip	0	0.0%

Feeling of beeing safe



4. Which of the following issues do you find to be the most distracting about street lighting?		
Answer Options (Can pick more than 1)	Response Count	%
Lamp was Inappropriately dim or fully off	3	17.6%
Lamp was cycling on/off	2	11.8%
Light flicker	1	5.9%
Audible noise	1	5.9%
Light Color	2	11.8%
Shadowing/Glare on objects in the street	6	35.3%
Light Trespass of street lighting (for instance into building)	1	5.9%
Other	1	5.9%
Skip	0	0.0%
5. If applicable, select one additional issue that has bothered you most in the past?		
Answer Options	Response Count	%
Initial cost of new lighting system	1	9.1%
Commissioning/ Troubleshooting of new adaptive lighting system	2	18.2%
Maintenance issues	1	9.1%
Early luminaire failure	3	27.3%
Other	0	0.0%
Not applicable / Skip	4	36.4%

Table 5. Demonstration Site Street Lighting - End User Responses

6. How frequently do you travel on Second Street?		
Answer option	Response Count	%
Hardly Ever	3	27.3%
Monthly	3	27.3%
Weekly	0	0.0%
Every other day	2	18.2%
Everyday	1	9.1%
Several Times per day	0	0.0%
Skip	2	18.2%
7.Pick the task you do most frequently when using Second Street at night:		
Answer option	Response Count	%
Drive motorized vehicle	7	63.6%
Bicycle	0	0.0%
Jog/Run	1	9.1%
Walk	1	9.1%
Other	0	0.0%
Skip	2	18.2%
8. How satisfied are you with Second Street lighting you have for that task at night?		
Answer option	Response Count	%
Highly Dissatisfied	0	0.0%
Dissatisfied	0	0.0%
Slightly Dissatisfied	0	0.0%
Indifferent	2	18.2%
Slightly Satisfied	0	0.0%
Satisfied	5	45.5%
Highly Satisfied	0	0.0%
Skip	4	36.4%
Satisfaction with 2nd Street lighting for task		
9. How safe do you feel with Second Street lighting you have for that task at night?		
Answer option	Response Count	%
Highly Dissatisfied	0	0.0%
Dissatisfied	0	0.0%
Slightly Dissatisfied	0	0.0%
Indifferent	2	18.2%

Slightly Satisfied	0	0.0%
Satisfied	5	45.5%
Highly Satisfied	1	9.1%
Skip	3	27.3%
Feeling of being safe		

Table 6. Demonstration Site Adaptive Controls - End User Responses

10. Have you noticed the adaptive function using 2nd street before today's site visit?		
Answer option	Response Count	%
Yes	1	9.1%
No	5	45.5 %
Not applicable /First time on site /Skip	5	45.5 %
11. How satisfied are you with the adaptive street lighting to support your use of 2nd Street?		
Answer option	Response Count	%
Highly Dissatisfied	0	0.0%
Dissatisfied	0	0.0%
Slightly Dissatisfied	0	0.0%
Indifferent	0	0.0%
Slightly Satisfied	0	0.0%
Satisfied	5	45.5 %
Highly Satisfied	2	18.2 %
Skip	4	36.4 %
Satisfaction with 2nd Street adaptive lighting		
12. How safe do you feel with the adaptive street lighting in place?		
Answer option	Response Count	%
Highly Dissatisfied	0	0.0%
Dissatisfied	0	0.0%
Slight Dissatisfied	0	0.0%
Indifferent	0	0.0%
Slight Satisfied	0	0.0%

Satisfied	5	45.5 %
Highly Satisfied	3	27.3 %
Skip	3	27.3 %

Chapter 7: Conclusions and Recommendations

This demonstration provides information useful for future installations of innovative occupancy sensors in outdoor applications, as well as providing general guidance for future installations of emerging technologies. Key areas with conclusions and recommendations for implementing innovative occupancy sensors in outdoor applications include energy savings system installation and troubleshooting, technology development, and end user acceptance.

Comparing the adaptive roadway lighting system configurations to an LED baseline without controls, the system owner can expect to achieve between 3 percent and 15 percent energy savings. More aggressive commissioning of the system, such as shorter time out and implementing a high-end trim, results in higher savings. Tuning photocell settings can make a difference of up to 250 hours of system use per year, or approximately six percent per year variance, adding sizeable consumption to the whole site.

Aggressive timeout settings for occupancy sensors are expected to yield additional energy savings without compromising safety. It is recommended that the manufacturer consider this feature for development in the next generation of their product.

Installation labor is one of the biggest costs associated with an adaptive lighting control system. Training of installers and contractors is advised as the emerging technologies differ from the traditional street lighting products. Development of manufacturer installation manuals for adaptive systems are recommended to mitigate expensive installation issues.

Development of plug-and-play hardware solutions for retrofit installations are highly recommended, as new construction and retrofit applications vary greatly in troubleshooting requirements. It is recommended to update photocell technologies for all retrofit projects, as the cost of additional trips to modify installed fixtures outweighs the cost of the photocell.

With recent product development efforts in the outdoor LED fixture and lighting control industries, commercialized technologies are now readily available to support adaptive networked lighting systems. Microwave sensor testing for this demonstration was conducted during a hot day, showing an improvement over conventional PIR technology for outdoor applications. PIR technology has limitations in hot environments where the temperature of the background and the temperature of the occupant are similar.

Approximately 45 percent of respondents reported they are satisfied with the new lighting system for their task most frequently performed along the demonstrate site; 18.2 percent are indifferent; 36.4 percent skipped the question. The majority of respondents reported they felt safe under the new lighting system. 45.5 percent of respondents reported they did not notice the adaptive control features of the demonstration site, that they were satisfied with the adaptive system and that they felt satisfied or highly satisfied with their feeling of safety while using the adaptive control system.

APPENDIX C-2: Technology Specifications

STR-LWY-3M-HT-02–06

LEDway® Street Light – Type III Medium – Horizontal Tenon Mount – 20–60 LEDs

Product Description

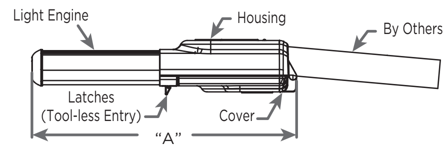
Luminaire housing is all aluminum construction. Standard luminaire utilizes terminal block for power input suitable for #2–#14 AWG wire. Luminaire is designed to mount on a 2" (51mm) IP, 2.375" (60mm) O.D. horizontal tenon and/or a 1.25" (32mm) IP, 1.66" (42mm) O.D. horizontal tenon (minimum 8" [203mm] in length) and is adjustable +/- 5˚ to allow for luminaire leveling (two axis T-level included).

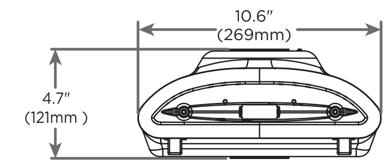
Performance Summary

- Utilizes BetaLED® Technology
- Patented NanoOptic® Product Technology
- Made in the U.S.A. of U.S. and imported parts
- **CRI:** Minimum 70 CRI
- **CCT:** 5700K (+/- 500K) Standard, 4000K (+/- 300K)
- **Limited Warranty†:** 10 years on luminaire/10 years on Colorfast DeltaGuard® finish
- **EPA and Weight:** Reference EPA and Weight spec sheet

Accessories

Field Installed Accessories	
XA-BRDSPK30 (20-30 LEDs)	**XA-XSLBLS30 (20-30 LEDs)**
XA-BRDSPK60 (40-60 LEDs) Bird Spikes for Light Engine	**XA-XSLBLS60 (40-60 LEDs)** External Backlight Shield
XA-BRDSPKHSG Bird Spikes for Housing	





LED Count (x10)	Dimension	Measurements
02	"A"	17.5" (443mm)
03	"A"	17.5" (443mm)
04	"A"	22.0" (559mm)
05	"A"	22.0" (559mm)
06	"A"	22.0" (559mm)

Ordering Information

Example: STR-LWY-3M-HT-02-E-UL-SV-525-OPTIONS

STR-LWY	3M	HT		E				
Product	**Optic**	**Mounting**	**LED Count (x10)**	**Version**	**Voltage**	**Color Options***	**Drive Current**	**Options** (For additional options see IP66 spec sheet)
STR-LWY	**3M** Type III Medium	**HT** Horizontal Tenon	**02** **03** **04** **05** **06**	**E**	**UL** Universal 120–277V **UH** Universal 347–480V	**SV** Silver (Standard) **BK** Black **BZ** Bronze **PB** Platinum Bronze **WH** White	**525**** 525mA **700** 700mA	**40K 4000K Color Temperature** - Color temperature per luminaire **DIM 0–10V Dimming** - Control by others - Refer to dimming spec sheet for details - Can't exceed specified drive current **F Fuse** - Not available with all ML options. Refer to ML spec sheet for availability with ML options - When code dictates fusing, use time delay fuse **HL Hi/Low (175/350/525 Dual Circuit Input)** - Refer to ML spec sheet for details - Sensor not included **N No Quick Disconnect Harness or Leveling Bubble** - Standard product features unless N option is specified **PD Power Door** - All connections between door and luminaire are shipped unconnected from the factory; door release spring included to open door automatically when the latches are released **R NEMA Photocell Receptacle** - Not available with all ML options. Refer to ML spec sheet for availability with ML options - Photocell by others - Intended for downlight applications at 0˚ tilt **SC Door Safety Tether** - Stainless steel aircraft cable **UTL Utility** - Includes exterior wattage label that reflects watts for the drive current selected. The ability to exceed selected drive current will be disabled

† See www.cree.com/lighting/products/warranty for warranty terms.
* Light engine portion of extrusion is not painted and will remain natural aluminum regardless of color selection. ** Available on luminaires with 30-60 LEDs.

Product Specifications

CONSTRUCTION & MATERIALS

- Housing is all aluminum construction
- Terminal block for power input suitable for #2–#14 AWG wire
- Luminaire is designed to mount on a 2" (51mm) IP, 2.375" (60mm) O.D. horizontal tenon and/or a 1.25" (32mm) IP, 1.66" (42mm) O.D. horizontal tenon (minimum 8" [203mm] in length) and is adjustable +/- 5˚ to allow for luminaire leveling (two axis T-level included)
- Exclusive Colorfast DeltaGuard® finish features an E-Coat epoxy primer with an ultra-durable powder topcoat, providing excellent resistance to corrosion, ultraviolet degradation and abrasion. Standard is silver. Bronze, black, white, and platinum bronze are also available

ELECTRICAL SYSTEM

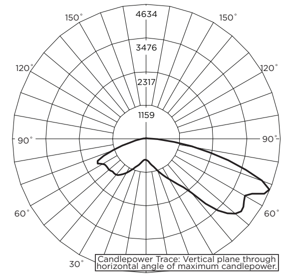
- **Input Voltage:** 120–277V or 347–480V, 50/60Hz, Class 1 drivers
- **Power Factor:** > 0.9 at full load
- **Total Harmonic Distortion:** < 20% at full load
- Quick disconnect harness suitable for mate and break under load provided on power feed to driver for ease of maintenance
- Integral 10kV surge suppression protection standard
- To address inrush current, slow blow fuse or type C/D breaker should be used

REGULATORY & VOLUNTARY QUALIFICATIONS

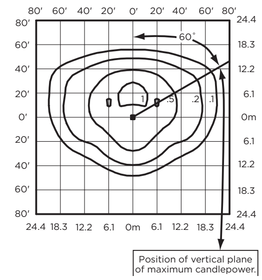
- cULus Listed
- Suitable for wet locations
- Consult factory for CE Certified products
- Meets CALTrans 611 Vibration testing and GR-63-CORE Section 4.4.1/5.4.2 Earthquake Zone 4
- Certified to ANSI C136.31-2001, 3G bridge and overpass vibration standards
- 10K surge suppression protection tested in accordance with IEEE/ANSI C62.41.2
- Luminaire and finish are endurance tested to withstand 5,000 hours of elevated ambient salt fog as defined in ASTM Standard B 117
- Product qualified on the DesignLights Consortium ("DLC") Qualified Products List ("QPL") when ordered without full backlight control shield
- RoHS Compliant
- Meets Buy American requirements within ARRA

Photometry

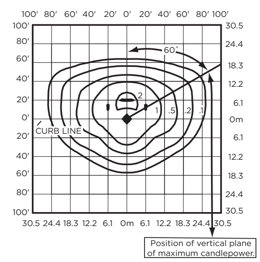
All published luminaire photometric testing performed to IESNA LM-79-08 standards by a NVLAP certified laboratory.



CESTL Test Report #: 2013-0068
STR-LWY-3M-**-06-E-UL-700-40K
Initial Delivered Lumens: 10,430



STR-LWY-3M-**-03-E-UL-700
Mounting Height: 25' (7.6m) A.F.G.
Initial Delivered Lumens: 5,600
Initial FC at grade



STR-LWY-3M-**-06-E-UL-700
Mounting Height: 25' (7.6m) A.F.G.
Initial Delivered Lumens: 11,076
Initial FC at grade

IES Files
To obtain an IES file specific to your project consult:
http://www.cree.com/lighting/tools-and-support/exterior-ies-configuration-tool

Lumen Output, Electrical, and Lumen Maintenance Data

Type III Medium Distribution													
LED Count (x10)	5700K		4000K		System Watts 120–480V	System Watts 347–480V	TOTAL CURRENT						50K Hours Projected Lumen Maintenance Factor @ 15˚C (59˚F)**
	Initial Delivered Lumens	BUG Ratings* Per TM-15-11	Initial Delivered Lumens	BUG Ratings* Per TM-15-11			120V	208V	240V	277V	347V	480V	
525mA @ 25˚C (77˚F)													
03	4,480	B1 U0 G1	4,314	B1 U0 G1	53	55	0.45	0.26	0.23	0.21	0.16	0.13	93%
04	5,985	B2 U0 G2	5,763	B2 U0 G2	66	71	0.56	0.33	0.29	0.26	0.21	0.16	
05	7,432	B2 U0 G2	7,156	B2 U0 G2	86	87	0.72	0.42	0.37	0.33	0.25	0.19	
06	8,861	B2 U0 G2	8,533	B2 U0 G2	100	103	0.84	0.49	0.43	0.38	0.30	0.22	
700mA @ 25˚C (77˚F)													
02	3,771	B1 U0 G1	3,631	B1 U0 G1	47	51	0.39	0.23	0.21	0.19	0.15	0.12	91%
03	5,600	B2 U0 G2	5,392	B2 U0 G2	70	73	0.59	0.34	0.30	0.27	0.21	0.16	
04	7,481	B2 U0 G2	7,204	B2 U0 G2	91	93	0.77	0.45	0.39	0.35	0.27	0.20	
05	9,290	B3 U0 G3	8,945	B2 U0 G2	113	115	0.96	0.55	0.48	0.43	0.33	0.25	
06	11,076	B3 U0 G3	10,666	B3 U0 G3	134	135	1.13	0.65	0.57	0.50	0.39	0.29	

* For more information on the IES BUG (Backlight-Uplight-Glare) Rating visit www.iesna.org/PDF/Erratas/TM-15-11BugRatingsAddendum.pdf.
** For recommended lumen maintenance factor data see TD-13. Calculated L_{70} based on 10,000 hours LM-80-08 testing: > 150,000 hours in accordance with guidelines describing "successors to previously tested subcomponents" (Section 5) per Sep 9, 2011 ENERGY STAR guidelines.
See http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/luminaires/ENERGY_STAR_Final_Lumen_Maintenance_Guidance.pdf.

Lumewave, Inc

TOP900-TN

TOP900-TN: Wireless Control Lighting Module

Lumewave's TOP900 wireless grid-smart lighting control module brings a new level of savings and control to outdoor lighting. The threaded nipple allows for installation directly to poles, fixtures, or other enclosures by simply attaching through the 1/2" knock out or opening. All power and control wiring can pass through the opening made by the removal of the photocell receptacle eliminating the need to penetrate fixtures.

The module is versatile enough to operate with LED and eHID ballast, plasma and induction light sources. Lumewave modules also provide feedback to users regarding the condition of lamps and ballasts, energy usage, power quality, and exact location of the fixture.

Fixtures can be addressed and grouped for unified on/off, high-low stepped dimming with off, tri-level stepped dimming with off, or 0-10 volt linear dim-ming operation. The TOP900 modules provide adjustable photocell thresholds as well as an time of day and astronomical clock with up to 9 time-of-day actions for additional savings.

Through the use of LumeStar front-end software, grouping and operational parameters are simply set. In addition, high-value indicators regarding the health of the fixture, lamp/ballast failure, energy consumption, and power quality are relayed back to the user on whatever schedule the user chooses. No longer will crews have to drive from location to location looking for outages and day burners. Work orders are automatically generated for the customer.

The Lumewave's Gateway Modules automatically select network and channels to insure interference-free operation. Gateways are highly reliable with a range of 5 to 10 miles (antenna dependent) and networks can have an unlimited number of devices on them. A minimum of one is required per site.

Four Gateways Interfaces are available:

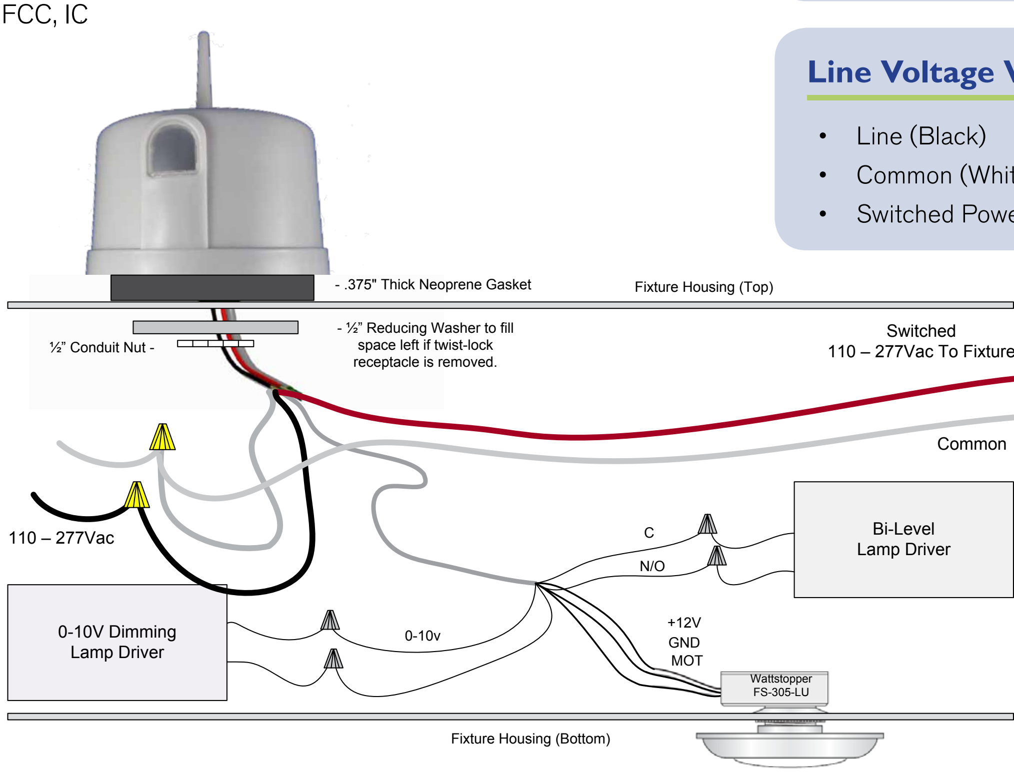
1. USB
2. Ethernet
3. Wi-Fi
4. Cellular

Control HID, LED, LEP & Induction Lamps

- Control Profiles and interfaces
  - Power to fixture on/off
  - Bi-level with OFF
  - Tri-level with OFF
  - 0-10V (sink) dimming control with 0V turning fixture power Off
  - Dimming control in 5% increments
- Control Events & Schedules
  - Daily control event schedules
  - Special event control schedule
  - Schedule up to 9 control events/day
  - Scheduled events based on time of day and/or astronomical time
  - Real-time commands and overrides
- Power Metering (Revenue Grade)
- Data Logging
- Failure detection and reporting
- Photocell thresholds synchronization
- Motion detector input
- Emergency call button input
- Over the air flashing (program updates)
- Lumen output depreciation detection and reporting (Coming Soon)
- Diagnostics

Electrical Specifications

- Replaces existing photocell & receptacle
- No need to penetrate fixture to pull wires
- All wiring routed through threaded 1/2" nipple
- Operating Voltage: 90-305Vac 50/60Hz
- Operating Temperature: -40C to +70C
- Fixture Power Contact: 1000W/1800VA
- Dimming: 0-10V (Sink)
- Failsafe: Power ON, Lamp High, 0-10V = 100%
- Motion detector input
- Emergency Call Button Input
- Photocell daytime override
- Tilt sensor for knock-down alert (Optional)
- Real-time Clock w/battery backup
- Programmable Time of day and/or Astronomical time control events and schedules
- Distributed process – Event schedules executed at unit. No need for frontend to be on line
- Real-time overrides of all control functions
- Real-time (demand incident) overrides of all schedules
- IP65
- ANSI 136.10
- FCC, IC



Wireless Specifications

Wireless Standard: IEEE 802.15.4
Operating Frequency: 902–928Mhz
Spread Spectrum: Direct sequence
Channels: 10
RF power: Adjustable to +24DBM
Antenna: Internal/external 1/4 wave monopole
Range: Base station to TOP module = 5 miles LOS
Range: Module to module @ 25' AGL = 2.5 miles
Range Extender: Any TOP module can repeat messages to extend network range

Low Voltage Control Wiring

1. C - Dry Relay Contact (Bi-level Control)
2. N/O - Dry Relay Contact (Bi-level Control)
3. 0-10V
4. Motion Detector Input
5. Call Button Input
6. Relay Driver Output 1
7. Relay Driver Output 2
8. Relay Driver Output 3
9. +12V DC
10. Ground (DC)

Line Voltage Wiring

- Line (Black)
- Common (White)
- Switched Power (Red)

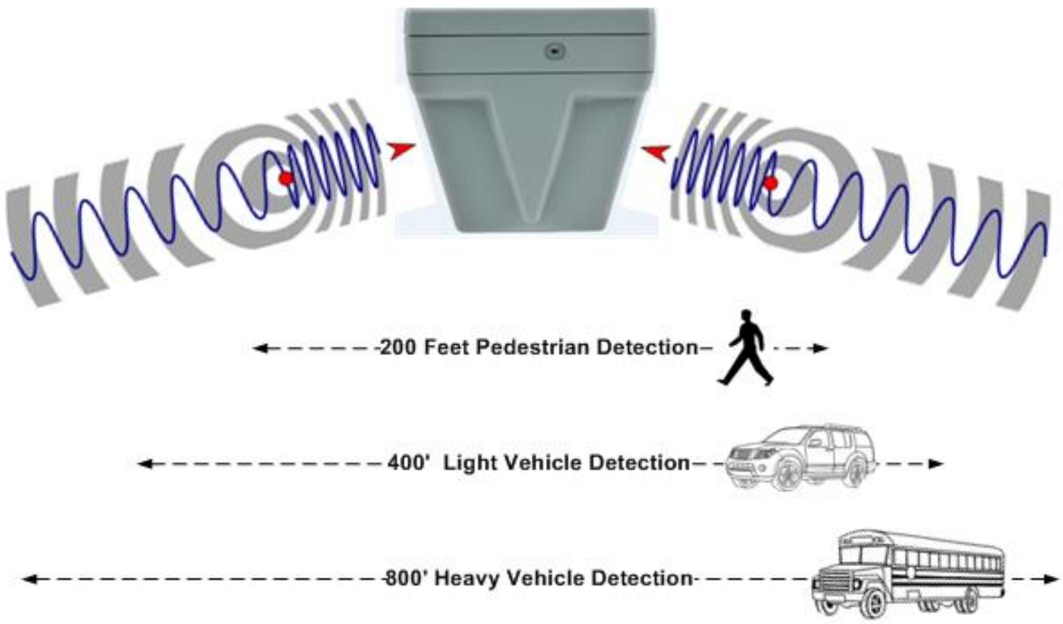
Lumewave MWX-LVE-180U

Outdoor Very Long Range Dual-Direction Microwave Sensor

Bluetooth Enabled Outdoor Radar based Sensor & Lighting Controller

Introducing the world's first Bluetooth enabled, long-range microwave sensor specifically designed for controlling outdoor street, parking lot, pathway and area lights.

The Lumewave MWX Sensor can distinguish between pedestrians and vehicles in real-time offering unique control opportunities. It can detect vehicles approaching at > 400' and Pedestrians at 100' and tell the difference!



Models

- MWX-LVE-180U (2-Way) Microwave Sensor Head
- MWX-PP Smart Power Pack (Used for stand-alone fixture control)

Control Configurations

- MWX-LVE-180U (2-Way) Microwave Sensor w/4-wire interface to Lumewave Controllers
- MWX-LVE-180U (2-Way) Microwave Sensor + MWX-PP (Smart Power Pack)
    - Use Smart Power Pack for stand-alone fixture control

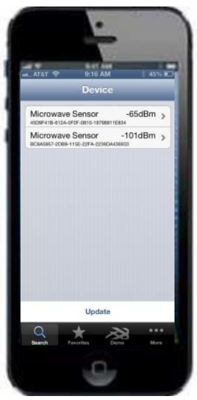
Sensor Mounting Configurations

- Mounting via vertical NTP 1/2" threaded nipple
- Mounting via right-angle NTP 1/2" threaded nipple

MWX Control application is available for iPhone and iPad

Downloadable "free" control application may be downloaded and run on iPhone/iPad which will use Bluetooth 4.0 to communicate with each sensor to set and modify its control settings. This will work much better than IR in the bright outdoor light and on fixtures high on poles.

iPhone/iPad application used to setup and manage sensors



Cable Connections

MWX-LVE-180U comes with 4-wire cable with connector

Lumewave Controller Connection

Use cable with connector that has flying-leads to connect to Lumewave Controller

MWX-PP

MWX-PP comes with cable coming from the MWX-PP that has a connector on end that plugs into MWX-LVE-180U cable connector.

Operating and Control Function Specifications

Note: When using MWX-LVE180U with Lumewave controller, access to many Bluetooth controlled functions are limited as Lumewave wireless controller handles them. In this case, the MWX-LVE180U is only a long range motion sensor. Active functions are highlighted below.

- Operating Voltage — 12Vdc (To be powered by UL listed Class 2 Power Source)
- Current — 60ma single sensor, 120ma dual direction
- Set Sensor Sensitivity — Direction A and/or B = High, Med, Low, Disable (individually)
- Set Motion Filter — Pedestrian, Vehicle, Both
- Set Low Level Output — 5% – 50% (.50 – 5.0V)
- Select High Level Output — 50% – 100% (5.0 – 10V)
- Set Bi-Level timeout — 2, 5, 10, 15, 20, 25, 30 minutes
- Tri-level timeout (Cutoff) — 30, 60, 90, 120minutes

- Photocontrol
  - Enable/Disable, Dual light detectors. Automatic differentiation between sensors
- Neighbor Control
  - Enable/Disable - Shares motion detection with other units within range for neighbor control
- Mechanical Noise Cancellation
  - Signal analysis cancels out non radar (mechanical) movement signals
- Test Enable/Disable
  - Test function with automatic timeout
- Inactivity Timeout 5, 10 minutes
- Mounting
  - 2 interchangeable tops supplied to provide multiple mounting configurations
- Environmental IP 65
- Certifications FCC

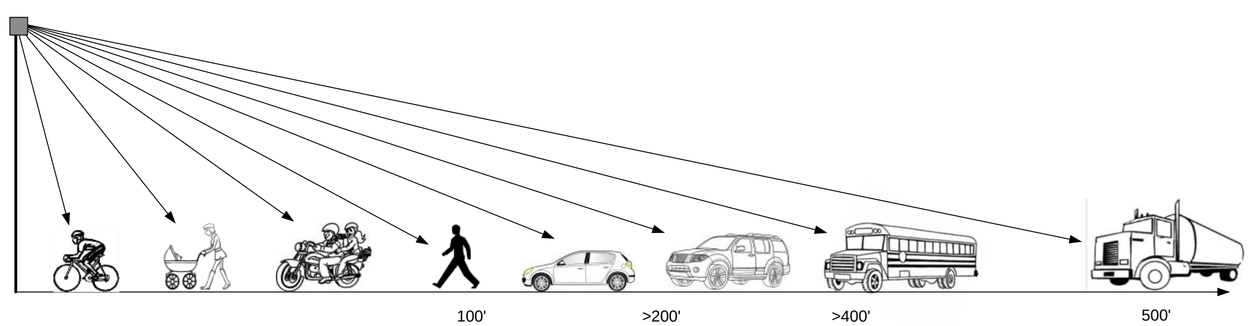
Detection Range at 20' or 30' mounting height

Range dependent on size and speed of target

- Pedestrian: 100'
- Small Vehicle: 165'
- Full size SUV: 200+
- Truck or Bus 400+

Microwave (FFT Doppler based) Sensor

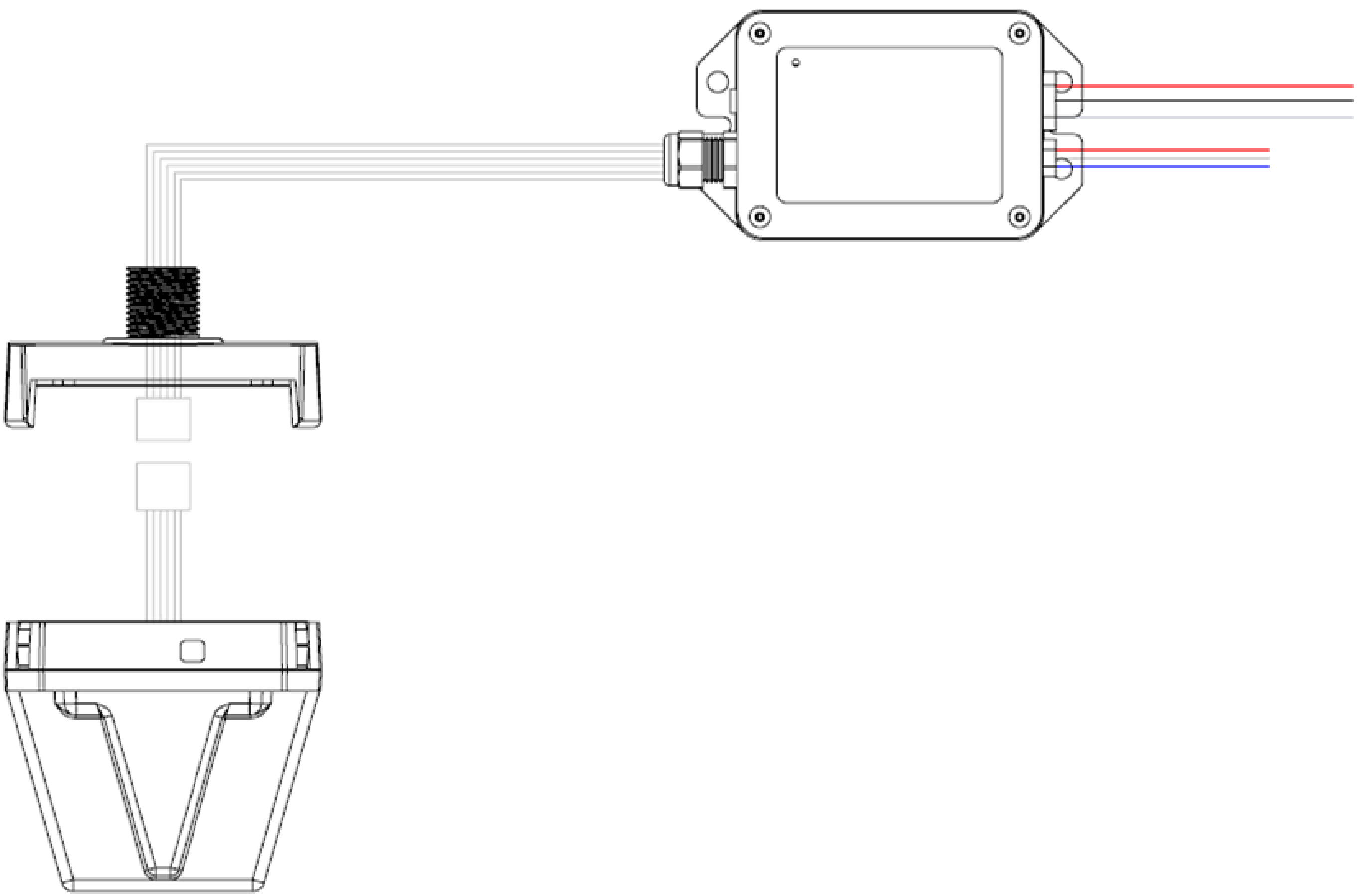
- Radar frequency: X Band, 10.250Ghz
- Power Output/Direction +17DBM, 100mw
- Power at 12Vdc 60ma/sensor/direction. 120ma when 2 sensor directions are active
- Detection Direction Single or Dual
- Filters Detects pedestrian and traffic movement together or individually (Selectable)
- Detection processing FFT Detects speed of pedestrian in real-time, simultaneously



MWX Power Pack

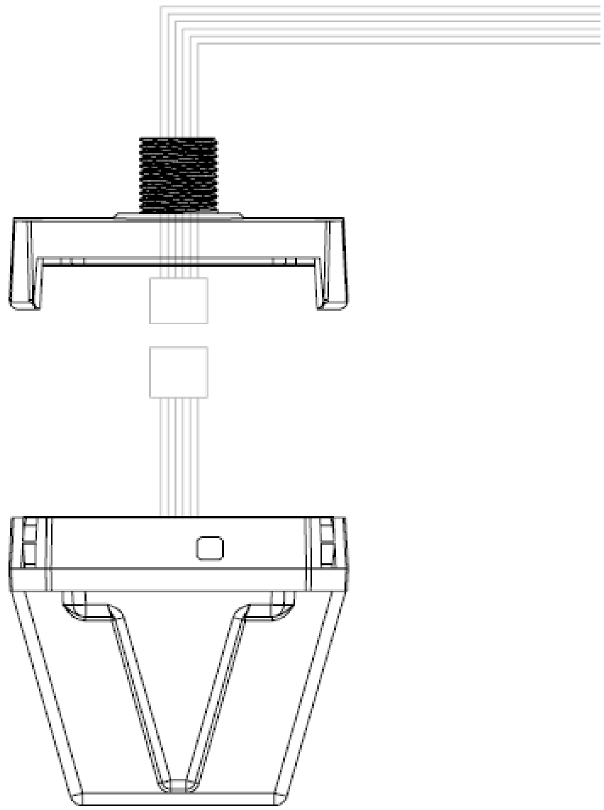
- Operating Voltage: 120 – 277Vac 50/60Hz
- Power switching: 10A, 277V General Purpose or Ballast
- Dimming Control: 0-10V (Sink) (or source)
- Size 3.50"X 2.50" x 1.00"
- Plastic UL 5VA Flame Retardant ABS, 3mm
- IP 65
- UL Listed

MWX-LVE-180U (2-Way) w/ MWXPP Power Pack



MWX-LVE-180U (2-Way) for connection to Lumewave (or other compatible) Controller.

4 wire connection cable with flying-leads

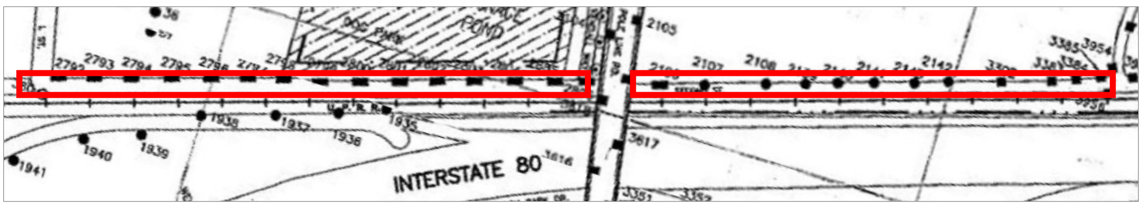


Appendix C-3: Site Survey

August 20th 2015 – Davis 2nd Street – Adaptive Streetlight Survey

Roadway and street lighting allows for the accurate and comfortable visual detection of nighttime hazards in a timely manner allowing occupants to react to the detected hazard. Properly designed roadway/street lighting[1] contributes to increased occupant safety and the proportional reduction of night time traffic accidents[2].

An advanced street lighting system has been installed on 2nd Street spanning Cantrill Drive to the corner of L Street.[3]



The lighting system includes 26 LED light fixtures and a networked control system of communication nodes and motion sensors for real-time “adaptation”.

Adaptive lighting delivers appropriate light levels based on the changing requirements of the exterior space as detected by sensors deployed in the space. This approach has proven to save significant energy in street applications.[4]

This survey is designed to the guidelines of Basic Ethical Principles for Human Research.
Participation is voluntarily.
Thank you for your time and valuable feedback!

If you have any further questions or feedback, please reach out to us:
California Lighting Technology Center, cltc@ucdavis.edu
Bernhard Goesmann, Associate Development Engineer, bgoesmann@ucdavis.edu

[1] ANSI/IES RP-8-14, “Roadway Lighting”, ISBN# 978-0-87995-299-0
[2] US-DoT, FHWA-HRT-14-051, "Design Criteria for Adaptive Roadway Lighting", July 2014, HRDS-20/07-14(WEB)E
[3] http://cltc.ucdavis.edu/networked-led-streetlights
[4] http://cltc.ucdavis.edu/publication/eyes-road

About you!

Gender:	*Male*		*Female*		*Other*	
Age Bracket:	*< 20*	*21-30*	*31-40*	*41-50*	*51-60*	*61+*

Name of your organization ______________________________

Role in organization / Job Title ______________________________

Other information you may want to share ______________________________

____

General Street Lighting Questions

Pick the task you do most frequently under street lighting:

1. *Drive a motorized vehicle*
2. *Bicycle*
3. *Jog/Run*
4. *Walk*
5. *Other:* ______________________________

How satisfied are you with general street lighting you have for that task at night?
(-3 = Highly Dissatisfied, 0 = Indifferent, 3 = Highly Satisfied)

-3 -2 -1 0 1 2 3 skip

How safe do you feel with general street lighting you have for that task at night?
(-3 = Highly Dissatisfied, 0 = Indifferent, 3 = Highly Satisfied)

-3 -2 -1 0 1 2 3 skip

Which of the following issues do you find to be the most distracting about street lighting? *(pick one)*

1. *Lamp was inappropriately dim or fully off*
2. *Lamp was cycling on/off*
3. *Light flicker*
4. *Audible noise*
5. *Light color*
6. *Shadowing/Glare on objects in the street*
7. *Light trespass of streetlighting (for instance into building)*
8. *Other:*____

If applicable, select one additional issue that has bothered you most in the past?

1. *Initial cost of new lighting system*
2. *Commissioning/Troubleshooting of a new adaptive lighting system*
3. *Maintenance issues*
4. *Early luminaire failure*
5. *Other:*____
6. *Not applicable*

Other general street lighting thoughts? ____

____

____

____

2nd Street Lighting System - Part 1

How frequently do you travel on 2nd Street?

Monthly *Weekly* *Every other day* *Every day* *Several times per day*

Pick the task you do most frequently when using 2nd Street at night:

1. *Drive a motorized vehicle*
2. *Bicycle*
3. *Jog/Run*
4. *Walk*
5. *Other:* ____

How satisfied are you with the current 2nd Street lighting you have for that task at night?
(-3 = Highly Dissatisfied, 0 = Indifferent, 3 = Highly Satisfied)

-3 -2 -1 0 1 2 3 skip

How safe do you feel with the current 2nd Street lighting you have for that task at night?
(-3 = Highly Dissatisfied, 0 = Indifferent, 3 = Highly Satisfied)

-3 -2 -1 0 1 2 3 skip

2nd Street Lighting System - Part 2

Have you noticed the adaptive function using the 2nd Street before today's site visit?

1. *Yes*
2. *No*
3. *Not Applicable (e.g., first visit to 2nd Street)*

How satisfied are you with the adaptive street lighting to support your use of 2nd Street?
(3 = Highly Dissatisfied, 0 = Indifferent, 3 = Highly Satisfied)

-3 -2 -1 0 1 2 3 skip

How safe do you feel with the adaptive street lighting in place?
(3 = Highly Dissatisfied, 0 = Indifferent, 3 = Highly Satisfied)

-3 -2 -1 0 1 2 3 skip

Other 2nd Street lighting thoughts? ______________________________

____

____

____

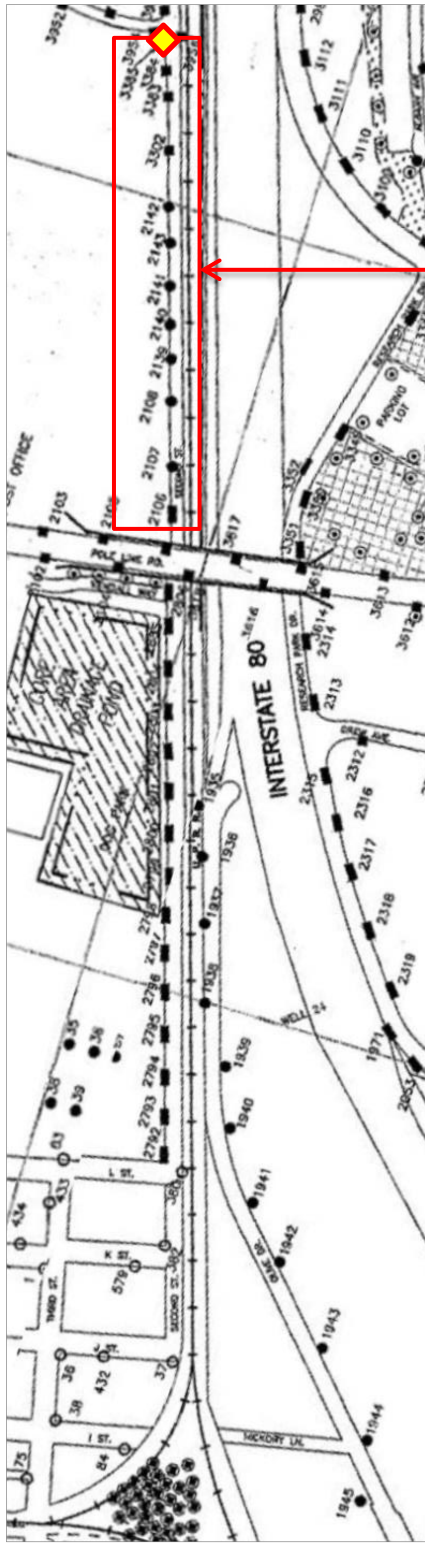
____

____

____

Appendix C-4: Installation Guide

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **EAST** – LID retrofit –BRN



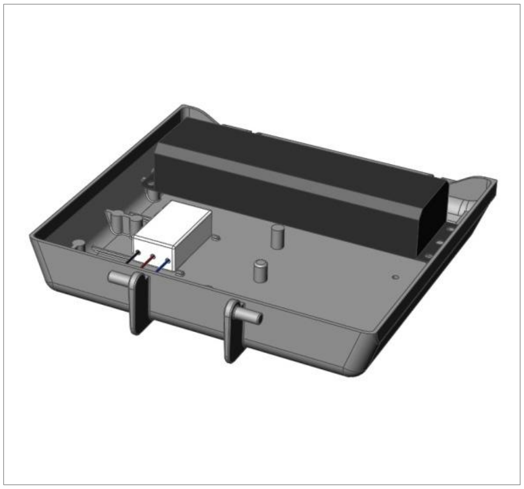
12x **East** of Pole Line overpass.

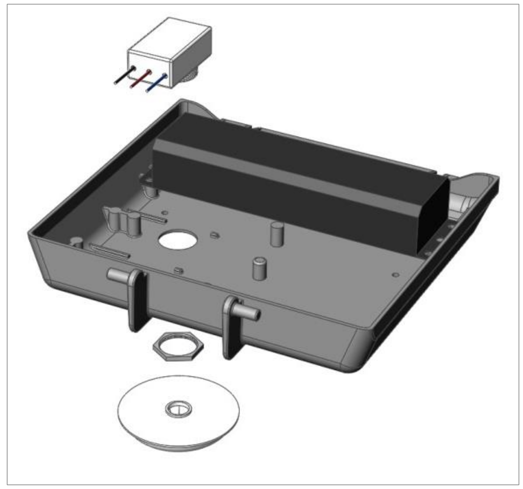
Sensor swap and wiring.

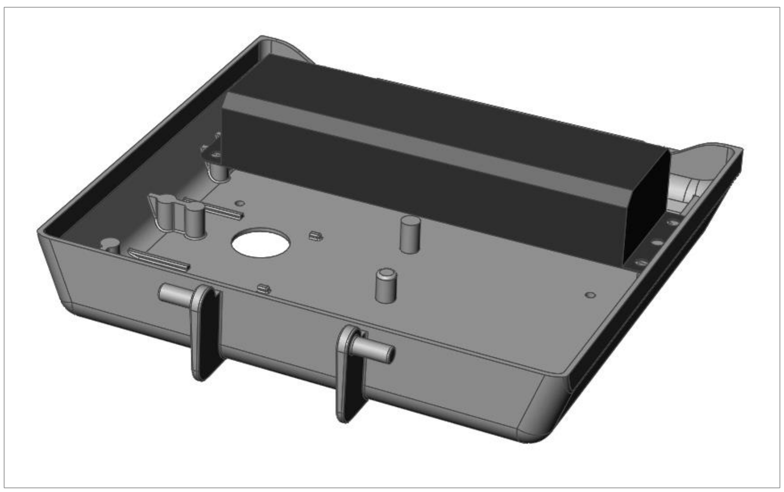
◇ 1x fully prepared lid #26 = pole #3385 for “rolling” installation start.

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **EAST** – LID retrofit –BRN

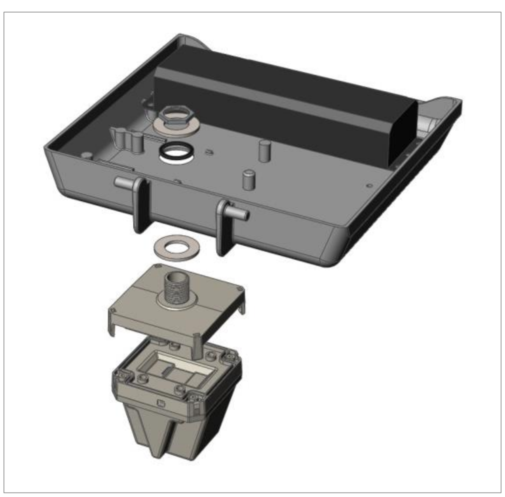
GOAL: take out old PIR-sensor (CAD view, no wires shown)

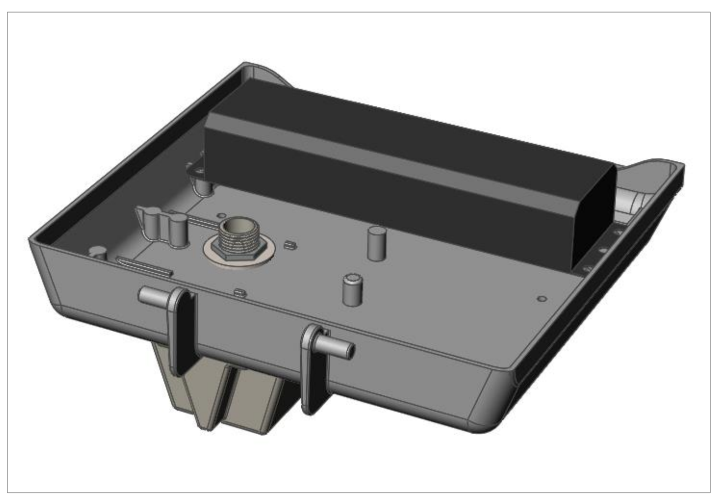






-> install new MWX-sensor:





2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **EAST** – LID retrofit –BRN

12 sensors total, 100% pre-tested:

Sensor are numbered (#15-26), with the corresponding Pole-ID# (2106-3385)

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **EAST** – LID retrofit –BRN

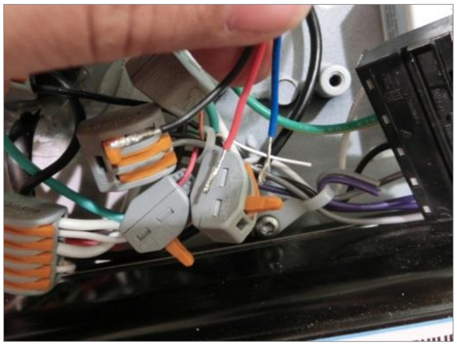
remove first lid (#26 at poleID# 3385):

install prepared lid #26/3385 and sensor

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **EAST** – LID retrofit –BRN

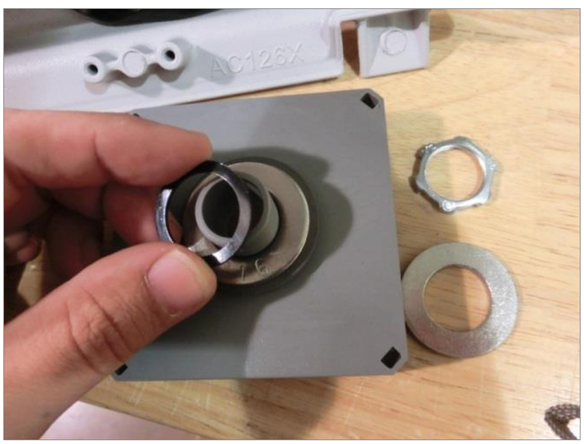
Use recovered lid to "roll-install":

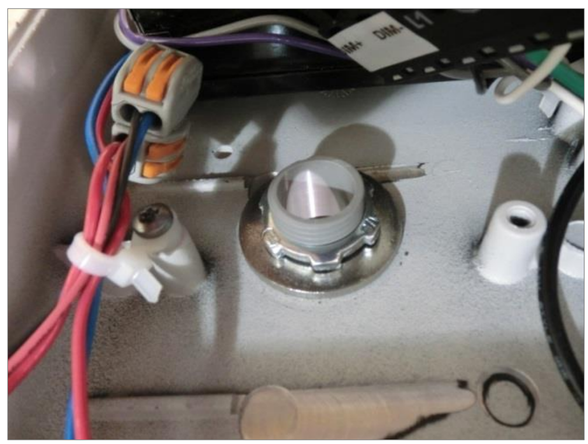
-disconnect BLACK, RED, BLUE of PIR sensor / unscrew lens & nut / take out PIR-sensor



-install MWX-sensor socket **IMPORTANT: sensor socket edge must be parallel to lid edge**

-> use SST washer, Plastic spacer ring and 2nd SST washer (washers & nuts supplied by CLTC)

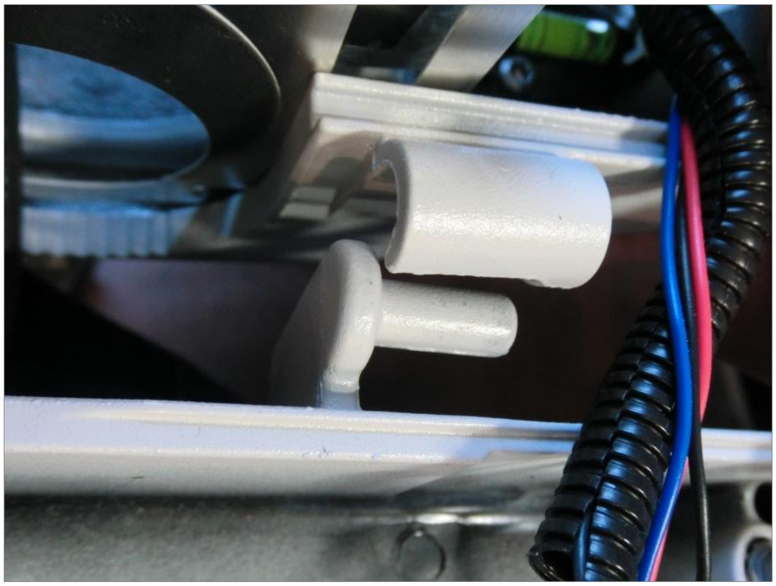




-install MWX wire strand & connect with WAGO's (BLACK, RED, BLUE) / install sensor with 4x screws

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **EAST** – LID retrofit –BRN

Be careful with the hinges, they do not have a retaining clip.

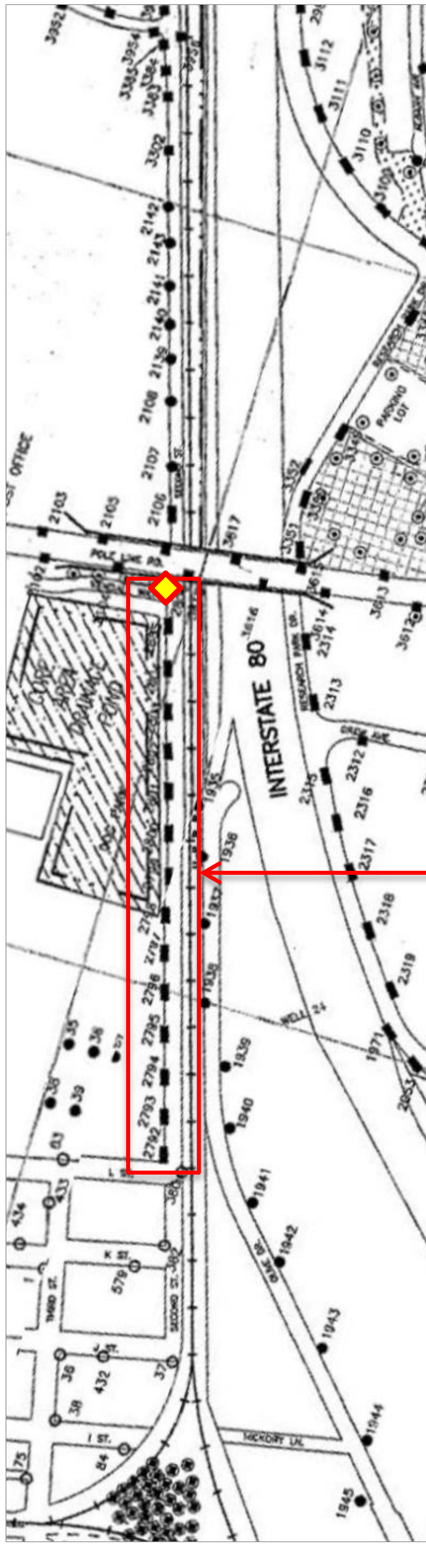


Make sure to close the lid clips all the way:

IMPORTANT:
Store the last collected lid from pole #2106 separate, this needs to be used later on pole #2798

TOOLS:
-T20 Torx
-5/16” Hex nut or wrench

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **WEST** – LID retrofit –BRN



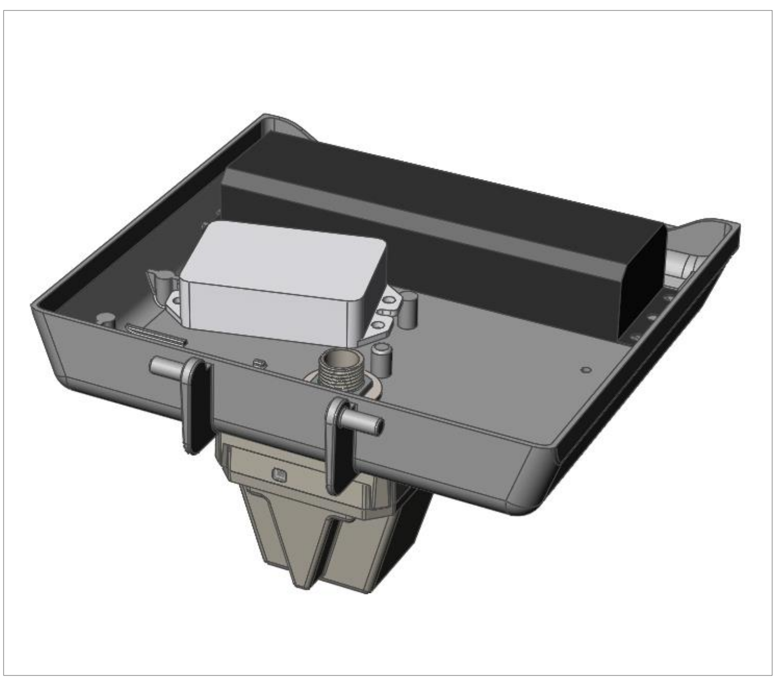
14x **West** of Pole Line overpass.

Door LED-driver swap to prepared exchange door and wiring.

1x fully prepared lid for #14 = pole #2806 for “rolling” installation start.

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **WEST** – LID retrofit –BRN

GOAL: transfer driver from old lid to new lid (CAD view, no wires shown)



2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **WEST** – LID retrofit –BRN

14 sensors total, 100% pre-tested:

Sensor are numbered (#01-14), with the corresponding Pole-ID# (2792-2806)

2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **WEST** – LID retrofit –BRN

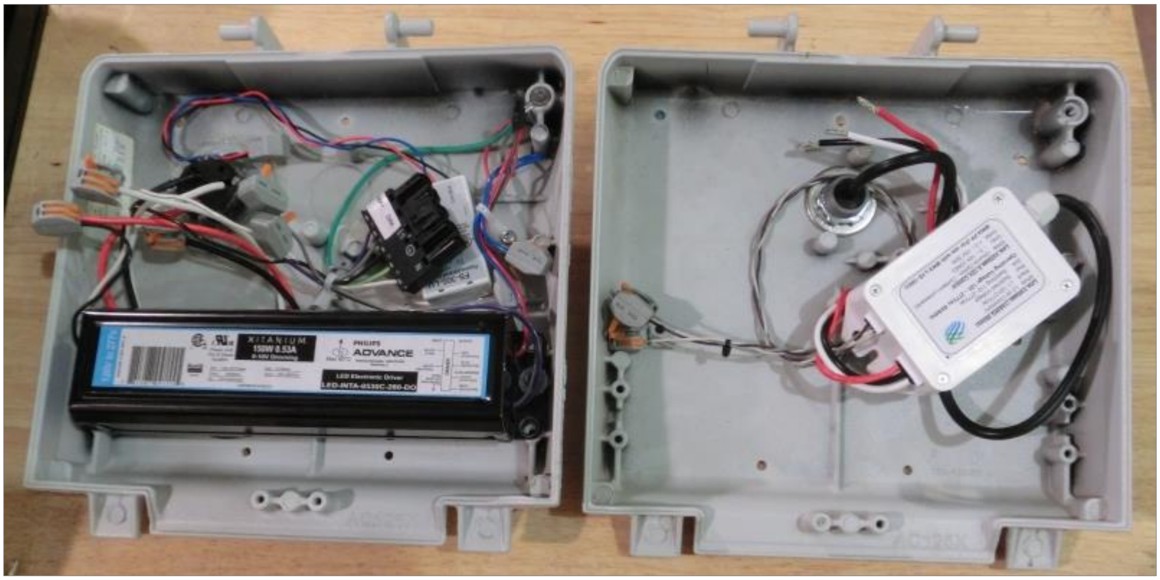
remove first lid #14 at pole #2806:

install prepared lid #14 at pole #2806 / install sensor

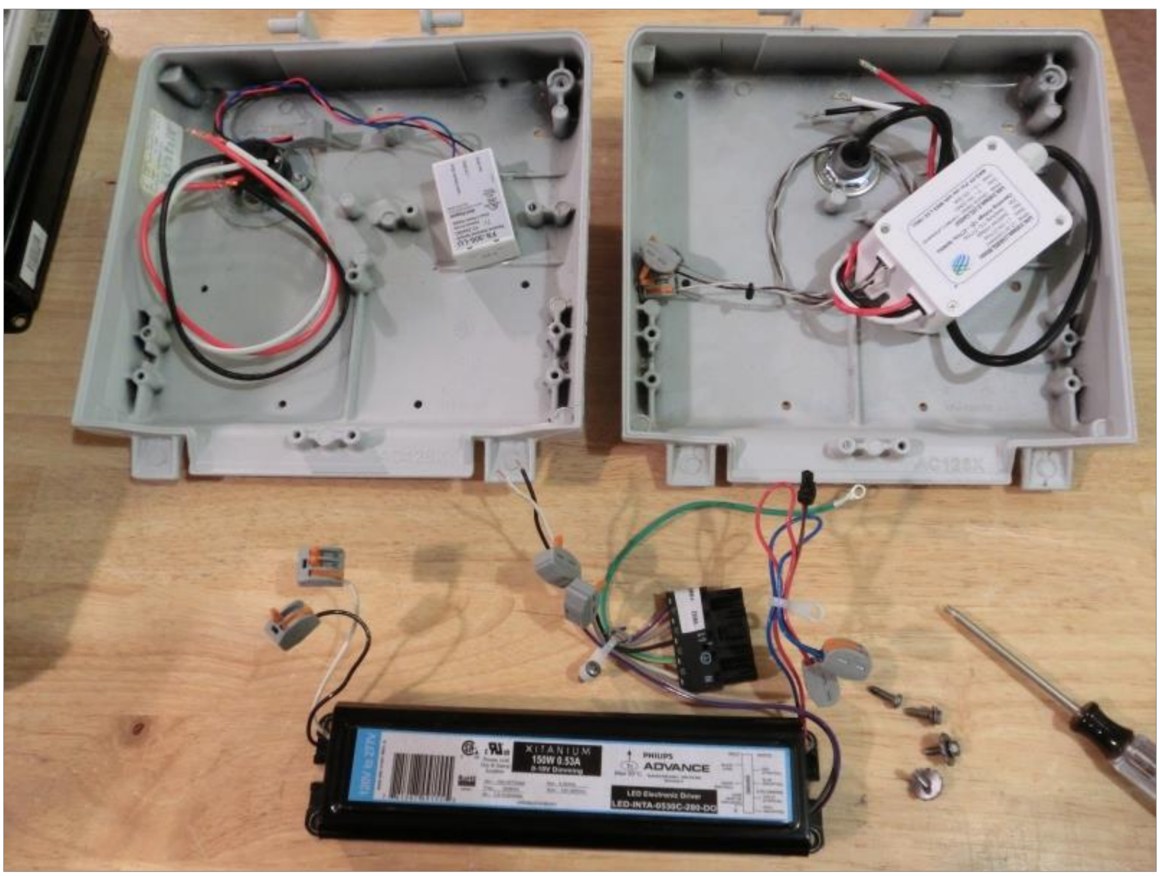
2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **WEST** – LID retrofit –BRN

Use recovered lid to “roll-install”:

13x lids are prepared with the Lumewave powerpack (PP) and the sensor base (lid on the right)

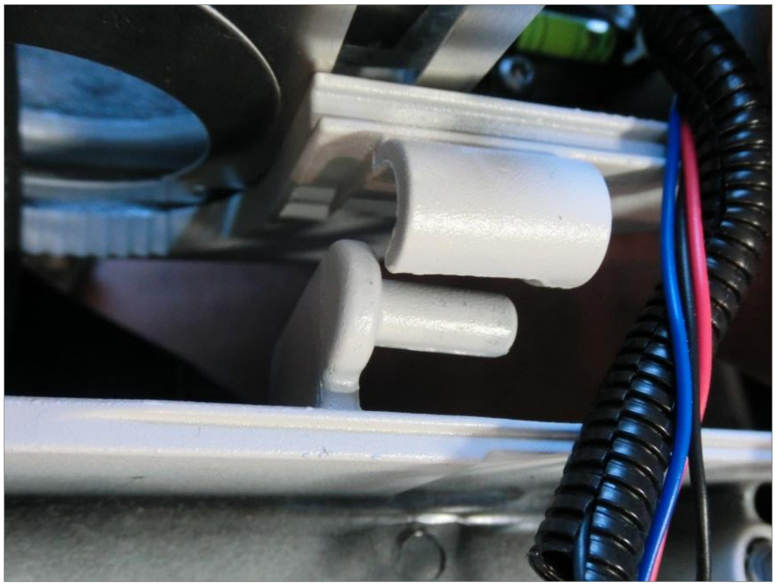


Transfer the driver and all wires from reclaimed lid -> to the prepared MWX-lid



2014.12.22/23 CASE-Davis, 2nd Street Installation Guide 01- **<u>WEST</u>** – LID retrofit –BRN

Be careful with the hinges, they do not have a retaining clip.



Make sure to close the lid clips all the way:

<u>IMPORTANT:</u>

<u>Collect the recovered & stripped lids (left) and hand back to CLTC staff</u>

<u>TOOLS:</u>

-T20 Torx

-5/16” Hex nut or wrench

Appendix C-5: Material Costs

CLTC

(Please Attach All Product Information)

Requestor's Information

Today's Date: 2014.Jun.27

Requestor's Name: Bernhard Goesmann

Ship To:

Business Name: CLTC

Address: 633 Pena Drive

City, State Davis

Zip Code 95618-1119

Ship to "ATTN OF" Bernhard Goesmann

Phone: (530) 747-3876

Product Information

Date Needed: ASAP

Shipping Preference: Pickup in Sacramento

Est. Cost $ 0

Vendor Name: Lumewave

Vendor Address: 1921 Arena Blvd, Sacramento, CA 95843

Phone: (916) 400-3535

Vendor Contact: Mark Keating, Stan Lynch

Fax: (678) 559-0337

Product Info:

ITEM #	QTY	UNIT OF ISSUE	DESCRIPTION	ACCOUNT NO.	CATALOG NO.	UNIT PRICE	TOTAL PRICE
1	27	1 pcs	Lumewave MWX-LVE-180U sensor	CASE-QDP		150	4050
2	14	1 pcs	Lumewave MWXPP, sensor power pack	CASE-QDP		40	560
3	1		Tax (8%)			368.8	368.8
4							0
5							0
						TOTAL	4978.8

Please copy this form to include additional line items.

Purpose of Expense(s): CASE-QDP / 2nd Street hardware

Supervisor Approval:

Keith Graeber or Kelly Cunningham

Program Approval:

Cori Jackson

OR email with written authorizations attached.

To Be Completed by Purchasing Agent

Date Sent to Purchasing:

DPO/PO/PR Number:

DaFIS Doc#

P-CARD:

Date:

CONTACT:

CONFIRM:

Country Bear Electric, Inc

P.O. Box 1016
Dixon, CA 95620
Phone (707) 678 1869
Fax (707) 678 0430

Invoice

DATE	INVOICE #
8/4/2015	14-4251

BILL TO
California Lighting Technology Center 633 Pena Dr. Davis, CA 95616

JOB NAME
2nd St.

TERMS	DUE DATE
Net 30	9/3/2015

ITEM	DESCRIPTION	QTY	AMOUNT
Installation	From Cantrill Drive intersection to the Pole Line Pedestrian Bridge, and consists of 4 LED streetlights. A number (TBD) of these fixtures need to be trouble shot. The affected fixtures need to be taken from the pole, brought to ground and a CLTC staff member will review the wiring harness, driver and overall state of the fixture. Possibly a new RF node (provided by CLTC) will be installed by CLTC before the fixture will be re-attached to the pole tenon. No additional installation hardware is expected for the installation team.		260.00
Installation	From the Pole Line Pedestrian Bridge to L Street intersection, and consists of 13 LED Streetlights. These existing fixtures will be modified with a new power pack (provided by CLTC) for the recently installed sensor. The installation will be prepared by CLTC for a time efficient "rolling swap" with one pre-modified door/lid. The power packs and installation/wiring guide will be supplied. The drivers and necessary wiring of the currently installed doors/lids do NOT change, only the power pack will be exchanged and re-wired on site by CLTC staff. No additional installation hardware is expected for the installation team.		845.00
Installation	Provide traffic control. Traffic plan was not provided at time of bid. 2014 control plan will be basis for proposal based on (1) day traffic control. Provide encroachment permit.		5,200.00

We appreciate your business! Please record invoice numbers on all checks. Thank you!

Total	$6,305.00
Payments/Credits	$0.00
Balance Due	$6,305.00

ELECTRIC SCHEDULE LS-2

Sheet 1

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

APPLICABILITY: This schedule is applicable to services for lighting installations which illuminate streets, highways, and other outdoor ways and places where the Customer is a Governmental Agency (Agency) and owns the lighting fixtures, poles and interconnecting circuits. This schedule is also applicable for service to those installations where service is initially established in the name of a developer who has installed such systems as required by an Agency and, where ownership of facilities and responsibility for service will be transferred to an Agency. Where the Agency does not accept facilities or where no transfer is intended, service will be provided under an otherwise appropriate rate schedule and rule. Class C is closed to new installations and additional lamps in existing accounts.

TERRITORY: The entirety of PG&E's service territory.

RATES: The total monthly charge per lamp is equal to the sum of the facility charge and the energy charge. The monthly charge per lamp used for billing is calculated using unrounded facility and energy charges.

Monthly facility charges include the costs of owning, operating and maintaining the various lamp types and size. Monthly energy charges are based on the kWh usage of each lamp.

Monthly energy charges per lamp are calculated using the following formula: (Lamp wattage + ballast wattage) x 4,100 hours/12 months/1000 x streetlight energy rate per kilowatt hour (kWh). Ballast wattage = ballast factor x lamp wattage.

Total bundled monthly facility and energy charges are shown below.

The various ballast wattages used in the monthly energy charge calculations can be found in the Ballast Factor table following the monthly energy charges. Ballast factors are averaged within each grouping (range of wattages). The same ballast factor is applied to all of the lamps that fall within its watt range. Applicant or Customer must provide third party documentation where manufacturer's information is not available for rated wattage consumption before PG&E will accept lamps for this schedule.

Direct Access (DA) and Community Choice Aggregation (CCA) charges shall be calculated in accordance with Condition 14, Billing, below. (T)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 2

RATES: (Cont'd.)

Facilities Charge Per Lamp Per Month

CLASS:	A	C***
	PG&E supplies energy and service only.	PG&E supplies the energy and maintenance service as described in Special Condition 8
	$0.206	$2.382

Energy Charge Per Lamp Per Month
All Night Rates

Nominal Lamp Rating:

LAMP WATTS	kWh per MONTH	AVERAGE INITIAL LUMENS*	Per Lamp Per Month: All Classes		Half-Hour Adjustment	
INCANDESCENT LAMPS:						
58	20	600	$3.009	(R)	$0.137	
92	31	1,000	$4.664	(R)	$0.212	
189	65	2,500	$9.779	(R)	$0.445	
295	101	4,000**	$15.195	(R)	$0.691	(R)
405	139	6,000**	$20.913	(R)	$0.951	(R)
620	212	10,000**	$31.895	(R)	$1.450	(R)
860	294	15,000**	$44.232	(R)	$2.011	(R)
MERCURY VAPOR LAMPS:						
40	18	1,300	$2.708	(R)	$0.123	
50	22	1,650	$3.310	(R)	$0.150	(R)
100	40	3,500	$6.018	(R)	$0.274	
175	68	7,500	$10.231	(R)	$0.465	(R)
250	97	11,000	$14.594	(R)	$0.663	(R)
400	152	21,000	$22.868	(R)	$1.039	(R)
700	266	37,000	$40.020	(R)	$1.819	(R)
1,000	377	57,000	$56.720	(R)	$2.578	(R)

---

* Latest published information should be consulted on best available lumens.

** Service for incandescent lamps over 2,500 lumens will be closed to new installations after September 11, 1978.

*** Closed to new installations and new lamps on existing circuits, see Condition 8A.

(Continued)

ELECTRIC SCHEDULE LS-2 Sheet 3
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

RATES: (Cont'd.)

LAMP WATTS	kWh per MONTH	AVERAGE INITIAL LUMENS	All Classes		Half-Hour Adjustment	
HIGH PRESSURE SODIUM VAPOR LAMPS AT: 120 VOLTS						
35	15	2,150	$2.257	(R)	$0.103	
50	21	3,800	$3.159	(R)	$0.144	
70	29	5,800	$4.363	(R)	$0.198	(R)
100	41	9,500	$6.168	(R)	$0.280	(R)
150	60	16,000	$9.027	(R)	$0.410	(R)
200	80	22,000	$12.036	(R)	$0.547	(R)
250	100	26,000	$15.045	(R)	$0.684	(R)
400	154	46,000	$23.169	(R)	$1.053	(R)
HIGH PRESSURE SODIUM VAPOR LAMPS AT: 240 VOLTS						
50	24	3,800	$3.611	(R)	$0.164	
70	34	5,800	$5.115	(R)	$0.233	
100	47	9,500	$7.071	(R)	$0.321	(R)
150	69	16,000	$10.381	(R)	$0.472	(R)
200	81	22,000	$12.186	(R)	$0.554	(R)
250	100	25,500	$15.045	(R)	$0.684	(R)
310	119	37,000	$17.904	(R)	$0.814	(R)
360	144	45,000	$21.665	(R)	$0.985	(R)
400	154	46,000	$23.169	(R)	$1.053	(R)
LOW PRESSURE SODIUM VAPOR LAMPS:						
35	21	4,800	$3.159	(R)	$0.144	
55	29	8,000	$4.363	(R)	$0.198	(R)
90	45	13,500	$6.770	(R)	$0.308	
135	62	21,500	$9.328	(R)	$0.424	(R)
180	78	33,000	$11.735	(R)	$0.533	(R)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 4

RATES: (Cont'd.)

LAMP WATTS	kWh per MONTH	AVERAGE INITIAL LUMENS	All Classes		Half-Hour Adjustment	
METAL HALIDE LAMPS:						
70	30	5,500	$4.514	(R)	$0.205	(R)
100	41	8,500	$6.168	(R)	$0.280	(R)
150	63	13,500	$9.478	(R)	$0.431	(R)
175	72	14,000	$10.832	(R)	$0.492	(R)
250	105	20,500	$15.797	(R)	$0.718	(R)
400	162	30,000	$24.373	(R)	$1.108	(R)
1,000	387	90,000	$58.224	(R)	$2.647	(R)
INDUCTION LAMPS:						
23	9	1,840	$1.354	(R)	$0.062	
35	13	2,450	$1.956	(R)	$0.089	
40	14	2,200	$2.106	(R)	$0.096	
50	18	3,500	$2.708	(R)	$0.123	
55	19	3,000	$2.859	(R)	$0.130	
65	24	5,525	$3.611	(R)	$0.164	
70	27	6,500	$4.062	(R)	$0.185	
80	28	4,500	$4.213	(R)	$0.192	
85	30	4,800	$4.514	(R)	$0.205	(R)
100	36	8,000	$5.416	(R)	$0.246	(R)
120	42	8,500	$6.245	(R)	$0.284	
135	48	9,450	$7.222	(R)	$0.328	(R)
150	51	10,900	$7.673	(R)	$0.349	
165	58	12,000	$8.726	(R)	$0.397	
200	72	19,000	$10.832	(R)	$0.492	(R)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 5

RATES: (Cont'd.)

LIGHT EMITTING DIODE (LED) LAMPS OR COMPARABLE LIGHTING TECHNOLOGY (unless otherwise specified in this tariff):

LAMP WATTS****	kWh per MONTH*****	Energy Rates Per Lamp Per Month		Half-Hour Adjustment	
0.00-5.00	0.9	$0.135	(R)	$0.006	
5.01-10.00	2.6	$0.391	(R)	$0.018	
10.01-15.00	4.3	$0.647	(R)	$0.029	
15.01-20.00	6.0	$0.903	(R)	$0.041	
20.01-25.00	7.7	$1.158	(R)	$0.053	
25.01-30.00	9.4	$1.414	(R)	$0.064	
30.01-35.00	11.1	$1.670	(R)	$0.076	
35.01-.40.00	12.8	$1.926	(R)	$0.088	
40.01-45.00	14.5	$2.182	(R)	$0.099	
45.01-50.00	16.2	$2.437	(R)	$0.111	
50.01-55.00	17.9	$2.693	(R)	$0.122	(R)
55.01-60.00	19.6	$2.949	(R)	$0.134	
60.01-65.00	21.4	$3.220	(R)	$0.146	(R)
65.01-70.00	23.1	$3.475	(R)	$0.158	
70.01-75.00	24.8	$3.731	(R)	$0.170	
75.01-80.00	26.5	$3.987	(R)	$0.181	(R)
80.01-85.00	28.2	$4.243	(R)	$0.193	
85.01-90.00	29.9	$4.498	(R)	$0.204	(R)
90.01-95.00	31.6	$4.754	(R)	$0.216	(R)
95.01-100.00	33.3	$5.010	(R)	$0.228	
100.01-105.00	35.0	$5.266	(R)	$0.239	(R)
105.01-110.00	36.7	$5.522	(R)	$0.251	
110.01-115.00	38.4	$5.777	(R)	$0.263	
115.01-120.00	40.1	$6.033	(R)	$0.274	(R)
120.01-125.00	41.9	$6.304	(R)	$0.287	
125.01-130.00	43.6	$6.560	(R)	$0.298	(R)
130.01-135.00	45.3	$6.815	(R)	$0.310	
135.01-140.00	47.0	$7.071	(R)	$0.321	(R)
140.01-145.00	48.7	$7.327	(R)	$0.333	(R)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 6

RATES: (Cont'd.)

LIGHT EMITTING DIODE (LED) LAMPS OR COMPARABLE LIGHTING TECHNOLOGY (unless otherwise specified in this tariff): (Cont'd.)

LAMP WATTS****	kWh per MONTH*****	Energy Rates Per Lamp Per Month		Half-Hour Adjustment	
145.01-150.00	50.4	$7.583	(R)	$0.345	
150.01-155.00	52.1	$7.838	(R)	$0.356	(R)
155.01-160.00	53.8	$8.094	(R)	$0.368	(R)
160.01-165.00	55.5	$8.350	(R)	$0.380	
165.01-170.00	57.2	$8.606	(R)	$0.391	(R)
170.01-175.00	58.9	$8.862	(R)	$0.403	(R)
175.01-180.00	60.6	$9.117	(R)	$0.414	(R)
180.01-185.00	62.4	$9.388	(R)	$0.427	(R)
185.01-190.00	64.1	$9.644	(R)	$0.438	(R)
190.01-195.00	65.8	$9.900	(R)	$0.450	(R)
195.01-200.00	67.5	$10.155	(R)	$0.462	
200.01-205.00	69.2	$10.411	(R)	$0.473	(R)
205.01-210.00	70.9	$10.667	(R)	$0.485	(R)
210.01-215.00	72.6	$10.923	(R)	$0.497	
215.01-220.00	74.3	$11.178	(R)	$0.508	(R)
220.01-225.00	76.0	$11.434	(R)	$0.520	(R)
225.01-230.00	77.7	$11.690	(R)	$0.531	(R)
230.01-235.00	79.4	$11.946	(R)	$0.543	(R)
235.01-240.00	81.1	$12.201	(R)	$0.555	(R)
240.01-245.00	82.9	$12.472	(R)	$0.567	(R)
245.01-250.00	84.6	$12.728	(R)	$0.579	(R)
250.01-255.00	86.3	$12.984	(R)	$0.590	(R)
255.01-260.00	88.0	$13.240	(R)	$0.602	(R)
260.01-265.00	89.7	$13.495	(R)	$0.613	(R)
265.01-270.00	91.4	$13.751	(R)	$0.625	(R)
270.01-275.00	93.1	$14.007	(R)	$0.637	(R)
275.01-280.00	94.8	$14.263	(R)	$0.648	(R)
280.01-285.00	96.5	$14.518	(R)	$0.660	(R)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 7

RATES: (Cont'd.)

LIGHT EMITTING DIODE (LED) LAMPS OR COMPARABLE LIGHTING TECHNOLOGY (unless otherwise specified in this tariff): (Cont'd.)

LAMP WATTS****	kWh per MONTH*****	Energy Rates Per Lamp Per Month		Half-Hour Adjustment	
285.01-290.00	98.2	$14.774	(R)	$0.672	(R)
290.01-295.00	99.9	$15.030	(R)	$0.683	(R)
295.01-300.00	101.6	$15.286	(R)	$0.695	(R)
300.01-305.00	103.4	$15.557	(R)	$0.707	(R)
305.01-310.00	105.1	$15.812	(R)	$0.719	(R)
310.01-315.00	106.8	$16.068	(R)	$0.730	(R)
315.01-320.00	108.5	$16.324	(R)	$0.742	(R)
320.01-325.00	110.2	$16.580	(R)	$0.754	(R)
325.01-330.00	111.9	$16.835	(R)	$0.765	(R)
330.01-335.00	113.6	$17.091	(R)	$0.777	(R)
335.01-340.00	115.3	$17.347	(R)	$0.789	(R)
340.01-345.00	117.0	$17.603	(R)	$0.800	(R)
345.01-350.00	118.7	$17.858	(R)	$0.812	(R)
350.01-355.00	120.4	$18.114	(R)	$0.823	(R)
355.01-360.00	122.1	$18.370	(R)	$0.835	(R)
360.01-365.00	123.9	$18.641	(R)	$0.847	(R)
365.01-370.00	125.6	$18.897	(R)	$0.859	(R)
370.01-375.00	127.3	$19.152	(R)	$0.871	(R)
375.01-380.00	129.0	$19.408	(R)	$0.882	(R)
380.01-385.00	130.7	$19.664	(R)	$0.894	(R)
385.01-390.00	132.4	$19.920	(R)	$0.905	(R)
390.01-395.00	134.1	$20.175	(R)	$0.917	(R)
395.01-400.00	135.8	$20.431	(R)	$0.929	(R)

**** Wattage based on total consumption of lamp and driver. Customer may be required to provide verification of total energy consumption of lamp and driver upon request by PG&E.

***** Assumptions consistent with tariff, based on 4100 hours of operation for a full year; mid-point in range established by deducting 2.5 watts from highest wattage in range. The energy use calculation is: (high wattage in range-2.5 watts)x(4,100 hours/12 months/1000)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 8

RATES: (Cont'd.)

Ballast Factors by Lamp Type and Wattage Range

(L)

Watt Range			Ballast Factor
MERCURY VAPOR			
1	to	75	31.00%
76	to	125	17.07%
126	to	325	13.69%
326	to	800	11.22%
801	+		10.34%
LOW PRESSURE SODIUM VAPOR			
1	to	40	75.61%
41	to	75	54.32%
76	to	110	46.34%
111	to	160	34.42%
161	+		26.83%
METAL HALIDE			
1	to	85	25.44%
86	to	200	20.39%
201	to	375	22.93%
376	to	700	18.54%
701	+		13.27%

Watt Range			Ballast Factor
HIGH PRESSURE SODIUM VAPOR			
120 Volts			
1	to	40	25.44%
41	to	60	22.93%
61	to	85	21.25%
86	to	125	20.00%
126	+		17.07%
240 Volts			
1	to	60	40.49%
61	to	85	42.16%
86	to	125	37.56%
126	to	175	34.63%
176	to	225	18.54%
226	to	280	17.07%
281	to	380	12.35%
381	+		12.68%

(L)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

RATES: (Cont'd.)

TOTAL ENERGY RATES

Total Energy Charge Rate ($ per kWh) $0.15045 (R)

UNBUNDLING OF TOTAL ENERGY CHARGES

The total energy charge is unbundled according to the component rates shown below.

Energy Rate by Components ($ per kWh)		
Generation	$0.08711	
Distribution**	$0.04086	(I)
Transmission*	$0.01075	(I)
Transmission Rate Adjustments*	$0.00109	(R)
Reliability Services*	$0.00008	
Public Purpose Programs	$0.00769	
Nuclear Decommissioning	$0.00097	
Competition Transition Charge	$0.00006	
Energy Cost Recovery Amount	($0.00504)	
DWR Bond	$0.00526	
New System Generation Charge**	$0.00162	

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* Transmission, Transmission Rate Adjustments, and Reliability Service charges are combined for presentation on customer bills.

** Distribution and New System Generation Charges are combined for presentation on customer bills.

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 10

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS:

1. **TYPE OF SERVICE**: This schedule is applicable to multiple lighting systems to which PG&E will deliver current at secondary voltage. Multiple current will normally be supplied at 120/240 Volt, single-phase. In certain localities PG&E may supply service from 120/208 Volt, wye-systems, polyphase lines in place of 240 Volt service. Unless otherwise agreed, existing series current will be delivered at 6.6 amperes. Single-phase service from 480 Volt sources and series circuits will be available in certain areas at the option of PG&E when this type of service is practical from PG&E's engineering standpoint. All currents and voltages stated herein are nominal, reasonable variations being permitted.

   New lights will normally be supplied as multiple systems. Series service to new lights will be made only when it is practical from PG&E's engineering standpoint to supply them from existing series systems.

2. **SERVICE REQUIREMENTS**:

   a) **PHOTO CONTROLS**

   This rate schedule is predicated on an electronic type photo controls meeting ANSI standard C136.10, with a turn on value of 1.0 foot-candles and a turn off value of 1.5 foot-candles. Electro-mechanical or thermal type photo controls are not acceptable for this rate schedule.

   b) **LIGHT or POLE NUMBERING**

   As agreed upon by the parties, pole number sequencing and coding for single lights or multiple lights on a single pole, shall be provided by either party and must conform to PG&E’s billing system. Customer will provide physical numbering on lights or poles for LS-2 installations in order to facilitate accurate billing and inventory reporting. Numbering is required prior to energizing facilities. Numbering must be legible from the ground.

   c) **SERVICE REQUESTS**

   Service requests for installation and energizing of Customer's facilities may be submitted on forms 79-1007 or 79-1107. Removal or de-energizing of Customer's facilities may be requested on form 79-1008.

   d) **WATTAGE STICKERS REQUIRED**

   A wattage sticker, visible from the ground, of a size and type acceptable to PG&E showing total fixture energy use in watts for any lamps billed under LIGHT (T)
   EMITTING DIODE (LED) LAMPS OR COMPARABLE LIGHTING TECHNOLOGY, (T)
   nominal wattage rating (in watts) for induction lighting, or stickers meeting requirements of ANSI Standard C136.15 for other lamp types must be installed on each fixture.

(Continued)

SPECIAL CONDITIONS: (Cont'd.)

3. **SERVICE INSTALLATION** (L)

PG&E will establish service delivery points within close proximity to its distribution system.

a) **Overhead:** In an overhead area, a single drop will be installed. For an overhead to underground system, service will be established in a PG&E box at the base of the riser pole or other agreed upon location within close proximity. PG&E will connect Customer's conductors at the service delivery point.

b) **Underground:** In an underground area, service will be established at the nearest existing secondary box. Where no secondary facilities exist, a new service, transformer and secondary splice box, as required, will be installed in the shortest most practical configuration from the connection on the distribution line source. Customer shall install and own all facilities from the service delivery point on PG&E's system.

c) **Customer Installation Responsibility:** Customer shall install, own and maintain all facilities beyond the service delivery point. For PG&E's serving facilities, Customer or Applicant, at its expense, shall perform all necessary trenching, backfill and paving, and shall furnish and install all necessary conduit and substructures (including substructures for transformer installations, if necessary, for street lights only) in accordance with PG&E's specifications. Riser material shall be installed by PG&E at the Customer's expense. Upon acceptance by PG&E, ownership of the conduit and substructures shall vest in PG&E. Customer shall provide rights of way as provided in electric Rule 16.

d) **PG&E Installation Responsibility:** PG&E shall furnish and install the underground or overhead service conductor, transformers and necessary facilities to complete the service to the distribution line source, subject to the payment provisions of Special Condition 4. Only duly authorized employees of PG&E shall connect Customer's loads to, or disconnect the same from, PG&E's electrical distribution facilities.

e) **Rearrangements:** Customer or Applicant shall pay, in advance, PG&E's estimated cost for any relocation or rearrangement of PG&E's existing street light or service facilities requested by Customer or Applicant and agreed to by PG&E.

f) **Non-Conforming Load:** Applicant or Customer must be a governmental agency. Any load, other then the lighting loads listed in the Rate table above, is non conforming load. Non conforming load may be connected to customer circuits not to exceed 150 watts per circuit, or light for individually connected lights. Loads will conform to the requirements of Agreement form 79-1048 available on PG&E's web site, http://www.pge.com/tariffs/EF.SHTML#EF for electric forms. All other non conforming load connected to unmetered LS-2 facilities exceeding this limitation requires metering of the Customer's system at PG&E's service delivery point. (L)

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 12

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

4. **NON REFUNDABLE PAYMENT FOR SERVICE INSTALLATION**: (L)

   a) Customer or Applicant shall pay in advance the estimated installed cost necessary to establish a service delivery point. A one-time revenue allowance will be provided based on Customer's kWh usage and the distribution component of the energy rate posted in the Rate Schedule for the lamps installed. The total allowance shall be determined by taking the annual equivalent kWh times the Distribution component of this rate divided by the cost of service factor shown in Electric Rule 15.C.

   b) The allowance will only be provided where PG&E must install capital assets to connect load. No allowance will be provided where a simple connection is required. Only lights on a minimum 11 hour All Night (AN) schedule for permanent service shall be granted an allowance. Where Applicant received allowances based upon 11 hour AN operation, no billing adjustments, as otherwise provided for in Special Condition 7, shall be made for the first three (3) years following commencement of service.

   Line or service extensions in excess of the above shall be installed under special condition 9.

5. **TEMPORARY SERVICE:** Temporary services will be installed under electric Rule 13.

6. **ANNUAL OPERATING SCHEDULES**: The above rates for AN service assume 11 hours operation per night and apply to lamps which will be turned on and off once each night in accordance with a regular operating schedule selected by the Customer but not exceeding 4,100 hours per year. (L)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

7. **OPERATING SCHEDULES OTHER THAN ALL-NIGHT:** Rates for regular operating schedules other than full all-night will be the AN rate, plus or minus, respectively, the half-hour adjustment for each half-hour more or less than an average of 11 hours per night. This adjustment will apply only to lamps on regular operating schedules of not less than 1,095 hours per year, or 3 hours per night, and may be applied for 24-hour operation. Photo control devices used for more or less than AN must be approved by PG&E prior to adjustments in billing. (L)

8. **MAINTENANCE, ACCESS, CLEARANCES**

   a) Maintenance

      The C rates include all labor and material necessary for the inspection, cleaning, or replacement by PG&E of lamps and glassware. Replacement is limited to certain glassware such as is commonly used and manufactured in reasonably large quantities. A commensurate extra charge will be made for maintenance of glassware of a type entailing unusual expense. The Class C rate also includes all labor and material necessary for replacement by PG&E of photoelectric controls. Class C rates are closed to new installations and to additional lamps in existing accounts as of March 1, 2006.

   b) Under the grand fathered Class C rates, the following shall apply:

      1) At Customer's request, where PG&E's resources permit, PG&E will paint poles for Customer on a time and material basis. This service will only be offered for poles that have been designed to be painted.

      2) PG&E will Isolate any trouble in the Customer's system which has resulted in an outage or diminished light output.

      3) PG&E will make necessary repairs which do not require wiring replacement on accessible wiring between poles and on equipment and wiring in and on poles to keep the system in operating condition.

      4) PG&E will provide labor for the replacement of material such as ballasts, relays, fixtures, individual cable runs between poles where such runs are in conduit, and other individual parts of the system that are not capital items.

      5) Customer shall compensate PG&E for any material furnished by PG&E not included in 8.A. above. Customer must have been on Class C for this service.

      6) PG&E shall not be responsible for excavation or any major replacement of circuits, conduits, poles, or fixtures owned by the Customer.

      7) Tree trimming is the responsibility of the Customer for installation of new lights or for maintaining lighting patterns of existing lights. (L)

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 14

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

8. **MAINTENANCE, ACCESS, CLEARANCES** (Cont'd.): (L)

c) Access

Customer will maintain adequate access for PG&E's standard equipment used in maintaining facilities and for installation of its facilities. PG&E reserves the right to collect additional maintenance costs due to obstructed access or other conditions preventing PG&E from maintaining its equipment with standard operating procedures. Applicant or Customer shall be responsible for rearrangement charges as provided for in Special Condition 3.e.

d) Clearances

Customer applicant shall, at its expense, correct all access or clearance infractions, or pay PG&E its total estimated cost for PG&E to relocate facilities to a new location which is acceptable to PG&E. Failure to comply with corrective measures within a reasonable time may result in discontinuance of service in accordance with electric Rule 11. Applicant or Customer shall be responsible for tree trimming to maintain lighting patterns of existing lights. (L)

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 15

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

9. **LINE EXTENSIONS** (L)

   A. Where PG&E extends its facilities to street light installations in advance of subdivision projects where subdivision maps have been approved by local authorities, extensions will be installed under the provisions of electric Rule 15, except as noted below.

   B. Where PG&E extends its facilities to street light installations in the absence of any approved subdivision maps, applicant shall pay PG&E's estimated cost, plus cost of ownership and applicable tax. Standard form contract 62-4527, Agreement to Perform Tariff Schedule Related Work, shall be used for these installations.

10. **STREET LIGHT LAMPS – STANDARD AND NONSTANDARD RATINGS:** The rates under Class C are applicable to both standard and group replacement street lamps. (T) Standard and group replacement street lamps have reference only to street lamps having wattage and operating life ratings within three percent of those specified in the EEI-NEMA Standards for Filament Lamps Used in Street Lighting. Where Class A service is supplied to lamps of other ratings than those specified in EEI-NEMA Standards an adjustment will be made in the lamp rates proportionate to the difference between the wattage of the lamps and the standard lamps of the same lumen rating.

11. **ENERGY EFFICIENT STREET LIGHTS:** Where Customer permanently installs energy efficient street lights and total energy use cannot be verified through industry standard test results and customer requests that the energy efficient street lights be added to this tariff, customer may be required to provide specific performance data on the total energy consumption of the fixture (which includes controls, lamp and ballast or driver) as requested by PG&E.

12. **CONTRACT:** Except as otherwise provided in this rate schedule, or where lighting service is installed in conjunction with facilities installed under the provisions of Rules 15 or 16, standard form contract 62-4527, Agreement to Perform Tariff Schedule Related Work shall be used for installations, rearrangements or relocations.

13. **POLE CONTACT AGREEMENT:** Where Customer requests to have a portion or all Customer owned street lighting facilities in contact with PG&E's distribution poles, a Customer-Owned Streetlights PG&E Pole Contact Agreement (Form 79 938) will be required. (L)

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

14. **BILLING:** This Rate Schedule is subject to PG&E's other rules governing billing issues, as may be applicable. PG&E performs regular auditing as part of this rate schedule.

Limited testing of Energy Efficient Street Light Technology will be allowed under this Rate Schedule where a light of the type and wattage of the fixture and lamp to be tested are not presently included in the rate tables. Such test installations are subject to approval by PG&E. Following approval, test installations will be billed at the customer's currently billed rate. Customer will provide a monthly inventory of streetlights that will be tested. The format and content of the inventory must be approved by PG&E. The Company reserves the right to audit customer. PG&E also reserves the right to collect the cost of any such audit from the customer. Testing is limited to existing street light fixtures and the total energy consumption per fixture must not exceed current energy use per fixture. Additional energy efficient street light fixtures installed will also be subject to billing under the current rate upon the approval of PG&E. The test period will not exceed 12 months.

Bundled Service Customers receive supply and delivery service solely from PG&E. The Customer's bill is based on the Total Rate set forth above.

Transitional Bundled Service Customers take transitional bundled service as prescribed in Rules 22.1 and 23.1, or take bundled service prior to the end of the six (6) month advance notice period required to elect bundled portfolio service as prescribed in Rules 22.1 and 23.1. These customers shall pay charges for transmission, transmission rate adjustments, reliability services, distribution, nuclear decommissioning, public purpose programs, New System Generation Charges[1], the applicable Cost Responsibility Surcharge (CRS) pursuant to Schedule DA CRS or Schedule CCA CRS, and short-term commodity prices as set forth in Schedule TBCC.

Direct Access (DA) and Community Choice Aggregation (CCA) Customers purchase energy from their non-utility provider and continue receiving delivery services from PG&E. Bills are equal to the sum of charges for transmission, transmission rate adjustments, reliability services, distribution, public purpose programs, nuclear decommissioning, New System Generation Charges[1], the franchise fee surcharge, and the applicable CRS. The CRS is equal to the sum of the individual charges set forth below. Exemptions to the CRS are set forth in Schedules DA CRS and CCA CRS.

	DA / CCA CRS		
Energy Cost Recovery Amount Charge (per kWh)	($0.00504)	(R)	
DWR Bond Charge (per kWh)	$0.00526	(I)	
CTC Charge (per kWh)	$0.00006	(R)	
Power Charge Indifference Adjustment (per kWh)			
Pre-2009 Vintage	($0.00002)	(I)	
2009 Vintage	$0.00104	(R)	
2010 Vintage	$0.00111	(R)	
2011 Vintage	$0.00113	(R)	
2012 Vintage	$0.00112	(R)	
2013 Vintage	$0.00109	(R)	
2014 Vintage	$0.00107	(R)	
2015 Vintage	$0.00107	(N)	(N)

15. **DWR BOND CHARGE:** The Department of Water Resources (DWR) Bond Charge was imposed by California Public Utilities Commission Decision 02-10-063, as modified by Decision 02-12-082, and is property of DWR for all purposes under California law. The Bond Charge applies to all retail sales, excluding CARE and Medical Baseline sales. The DWR Bond Charge (where applicable) is included in customers' total billed amounts.

[1] Per Decision 11-12-031, New System Generation Charges are effective 1/1/2012.

Appendix C-5: References

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Appendix D: FDD Assessment Report

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Executive Summary

The 2006 California Commercial End Use Survey attributes roughly 29% of commercial electrical use to HVAC[1]. The majority of HVAC units in California appear to be packaged single zone equipment, at older vintages (2008 and older). The majority of the small and very small California commercial businesses do not perform periodic maintenance on HVAC systems. Heat pumps make up a minority, but significant amount of the heating equipment in California businesses.

Promoting sustained, optimal performance in the world of Heating, Ventilation, and Air Conditioning (HVAC) presents big opportunities as well as monumental challenges in supporting the efficiency goals of California. HVAC fault detection and diagnostics (FDD) is a crucial path to fully realizing sustained benefits of energy efficiency. FDD comprises a vast array of technologies that assist in identification of maintenance or repair needs using measurements and software intelligence[2]. In this, FDD continues to have a key role, with ample room for advancement. The understanding of FDD technologies has come a long way, but is still at the early stages. This project intends to explore select faults and FDD technologies applicable to a small commercial packaged rooftop unit (RTU) heat pump.

Overall, there exists a massive matrix of potential faults for the seemingly innocuous packaged rooftop unit air conditioner. These faults may come into existence in a variety of ways, made up of varying fault types, fault intensity/severity, fault combinations, system/component configurations, indoor/outdoor conditions, etc. This laboratory study focused on economizer, charge and airflow faults, anchored to a typical 5 ton RTU heat pump, under OD conditions representative of California climate zones. Four FDD units and the RTU charge protocol were subjected to a series of laboratory tests. The main areas for this study's findings include:

1. FDD performance for three units and RTU charge protocol under controlled, steady-state lab conditions under cooling mode operation
2. FDD performance for one unit under controlled, steady-state lab conditions under heating mode operation
3. FDD performance for one unit under economizer faults
4. The impacts of several common faults in single and multiple-fault scenarios

Generally, economizer FDD performance analysis is more binary in nature (diagnosed or not diagnosed). For charge and airflow faults, a fault impact target must be set to frame the analysis. Figure 1 and Table 1 illustrate an example of FDD performance results for all cooling mode tests, with the fault impact target also indicated.

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[1] http://www.energy.ca.gov/ceus/

[2] https://engineering.purdue.edu/HVACFDD/pdfs/Workshop_on_FDD_for_RTUs_Presentations/RTU_FDD_Introduction-Braun.pdf

Figure 1. FDD Outputs: All Tests, Cooling Mode

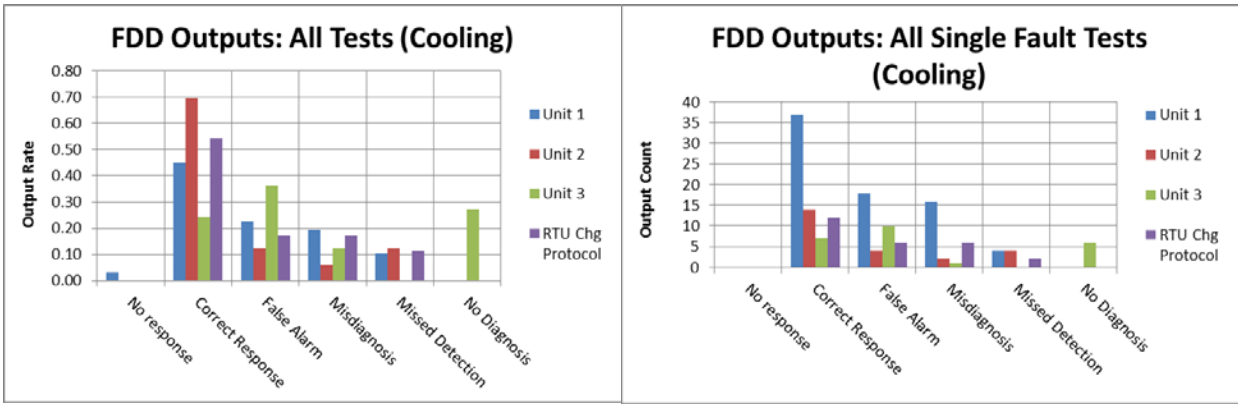


Table 1 – FDD Outputs: All Tests, Cooling Mode

Description	FDD Test Unit	Number of Tests	Tests that Exceed Fault Threshold	Sum of Total Outputs	Output Category	Output Rate	Output Count
All Cooling Mode Tests	Unit 1	33	19	98	No response	0.03	3
					Correct Response	0.45	44
					False Alarm	0.22	22
					Misdiagnosis	0.19	19
					Missed Detection	0.10	10
					No Diagnosis	0.00	0
	Unit 2			33	No response	0.00	0
					Correct Response	0.70	23
					False Alarm	0.12	4
					Misdiagnosis	0.06	2
					Missed Detection	0.12	4
					No Diagnosis	0.00	0
	Unit 3			33	No response	0.00	0
					Correct Response	0.24	8
					False Alarm	0.36	12
					Misdiagnosis	0.12	4
					Missed Detection	0.00	0
					No Diagnosis	0.27	9
	RTU Chg Protocol			35	No response	0.00	0
					Correct Response	0.54	19
					False Alarm	0.17	6
					Misdiagnosis	0.17	6
					Missed Detection	0.11	4
					No Diagnosis	0.00	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge.

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

For select OD restriction tests, unit 1 & 3 required overrides of high pressure readings to their max values.

The state of FDD technology today can assist in some key areas, but there are still many issues that reside outside the scope of FDD. It still remains to be seen what the valuation of FDD benefits currently is, and how far it can potentially go. This project has generated raw outputs of FDD performance, but additional steps to value these outputs needs to be pursued.

At this stage one cannot definitively assess what constitutes "good" FDD or "bad" FDD. It is cautioned to avoid the mindset of assuming that the goal of "good" FDD should be at/near 100% correct response count/rate (with 0% count/rate of other responses). This is an easy trap to fall into as it is an arbitrary, ideal notion, with no realistic foundation (You wouldn't make such a statement just as you would never make the statement that a “good” baseball player should be at/near a 100% batting average).

Introduction

Heating, Ventilation, and Air Conditioning (HVAC) fault detection and diagnostics (FDD) is a crucial path to fully realizing sustained benefits of energy efficiency (EE). FDD comprises a vast array of technologies that assist in identification of maintenance or repair needs using measurements and software intelligence[3]. These technologies can play various roles in enhancing the understanding of many HVAC systems and/or components, and ultimately understanding whether they are performing optimally. They help provide insight to:

- Verify proper installations
- Foster proactive, enhanced, ongoing maintenance strategies
- Assist in system troubleshooting

HVAC FDD technologies are generally made available as onboard or in-field technologies. Onboard technologies leverage sensors that permanently reside with the HVAC system while in-field technologies leverage portable sensors intended for short-term measurements. Onboard technologies may come as factory-installed options by the original equipment manufacturer, or supplied by a separate 3rd party. These technologies show ample opportunity to achieve and maintain significant energy and demand savings in support of strategic initiatives, goals, and policies across California. This project intends to explore select faults and FDD technologies applicable to a small commercial packaged rooftop unit (RTU) heat pump.

Figure 2 – Fault Detection and Diagnostics Technologies

3 https://engineering.purdue.edu/HVACFDD/pdfs/Workshop_on_FDD_for_RTUs_Presentations/RTU_FDD_Introduction-Braun.pdf

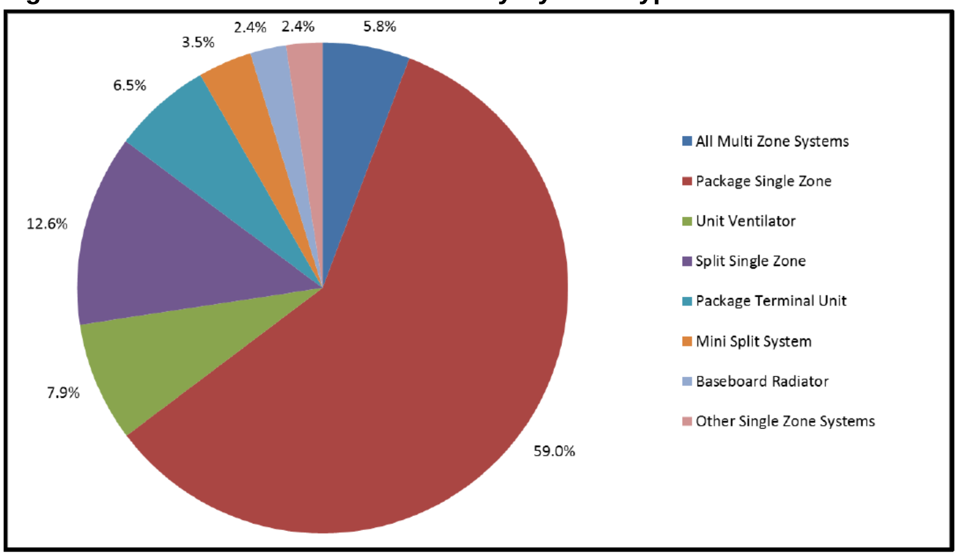
Background

The 2006 California Commercial End Use Survey attributes roughly 29% of commercial electrical use to HVAC. The California Commercial Saturation Study and the California Commercial Market Share Tracking Study help characterize the current state of affairs with regards to existing HVAC equipment. Figure 3 and Figure 4 illustrate the system type and age distribution of HVAC equipment surveyed in California. Table 2 characterizes the HVAC maintenance strategies, differentiated by IOU service territories.

Figure 5 illustrates the differences in maintenance strategies by business size. The saturation study also indicates that heat pumps make up 31% of heating in California businesses. ("For the CSS study, size categories were created based on annual electricity usage. Large sites have annual usage over 1,750,000 kWh, Medium have greater than 300,000 kWh and less than or equal to 1,750,000, Small have a maximum annual usage greater than 40,000 kWh and less than or equal to 300,000, and Very Small sites have annual usage less than or equal to 40,000 kWh."[4])

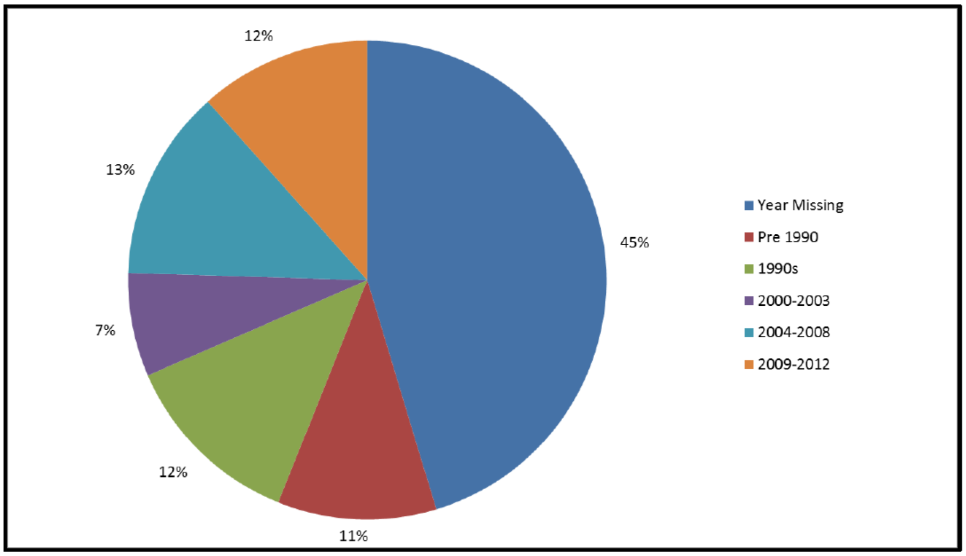
The majority of HVAC units in California appear to be packaged single zone equipment, at older vintages (2008 and older). The majority of the small and very small California commercial businesses do not perform periodic maintenance on HVAC systems. Heat pumps make up a minority, but significant amount of the heating equipment in California businesses.

Figure 3 – Distribution of HVAC Units by System Type[4]



* The results presented above have been weighted by site weight.

Figure 4 – Distribution of HVAC Units by Age[4]



* **The results presented above have been weighted by site weight.**

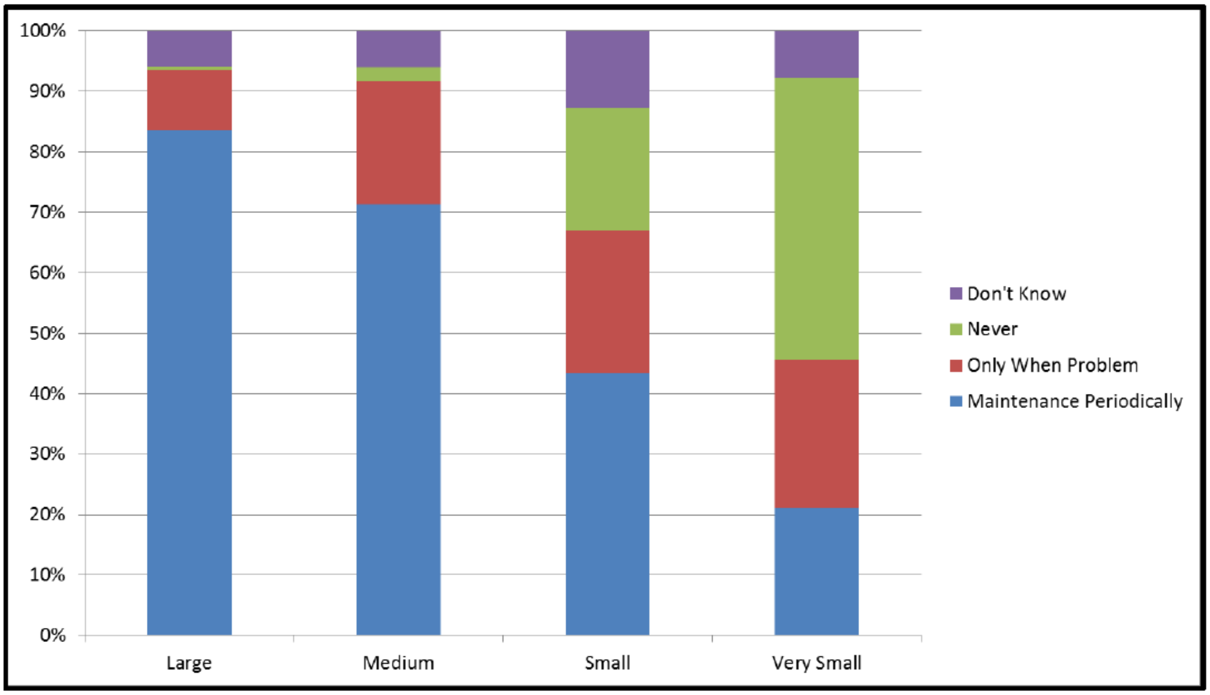
Table 2 – HVAC Maintenance Summary by CA IOU[4]

Maintenance Schedule	PG&E	SCE	SDG&E
Maintenance Periodically	35%	28%	30%
Only when Problem	25%	23%	24%
Never	33%	41%	26%
Don't Know	7%	8%	20%
Total	**100%**	**100%**	**100%**
n	**508**	**554**	**194**

* **The results presented above have been weighted by site weight.** Totals represent the count of surveyed sites, with HVAC, included in the analysis.

[4] California Commercial Saturation Study. August 26, 2014.

Figure 5 – Maintenance Summary by Business Size[4]



* **The results presented above have been weighted by site weight.**

The RTU heat pump is a seemingly simple, innocuous form of HVAC equipment. Upon closer, inspection in fact, contains a myriad of components that may accrue faults that can eventually lead to significant reductions in performance and efficiency. Table 3 illustrates a hierarchy of potential faults for a small commercial RTU heat pump. This hierarchy was developed via a failure modes analysis, comprised of elements from a WCEC technician survey, ASHRAE standard 180 maintenance checklists, FDD specs from a voluntary DOE High Performance Rooftop Unit challenge, California Building Energy Efficiency Standards, as well as from general experiences and conversations with various industry professionals. This list is not a final, static document. It contains elements from several sources that do not always use consistent characterizations and terminology. Efforts should continue to further improve the mapping of these faults into a cohesive whole. Establishing a consistent fault language and hierarchy would improve the way FDD technologies are understood.

Table 3 – Fault Failure Modes Analysis - 1

ID	Faults					
1	Air Conditioner / Heat Pump	Air-side Circuit	Indoor Section	Return/Supply openings	Obstruction	
2				Filter	Dirty	
3					Obstruction	
4					Improper fit	
5					Compromised housing seal integrity	
6				UV Lamp	Dirty/damaged	
7				Evaporator	Low Airflow	Fouling
8						Obstruction
9						Damaged Surfaces/Fins
10					Reduced heat transfer effectiveness (non-airflow)	Fouling
11						Damaged Surfaces/Fins
12				Indoor Section Fan	Variable Speed Drive	Improper Operation
13					Motor contactor	Pitting/other damage
14					Bearing	Wear
15					Belt	Wear
16						Improper Tension
17					Sheave	Wear
18						Improper Alignment
19					Fan blades	Dirty/damaged
20					Fan Housing	Dirty/damaged
21					Fan drive	Wear
22						Poor alignment
23						Poor bearing seating

Table 4 – Fault Failure Modes Analysis - 2

ID	Faults					
24	Air Conditioner / Heat Pump	Air-side Circuit	Indoor Section	Combustion chamber	Deterioration	
25					Leaks	
26					Moisture problems	
27					Condensation	
28					Combustion products	
29				Burner	Deterioration	
30					Leaks	
31					Moisture problems	
32					Condensation	
33					Combustion products	
34				Flue	Deterioration	
35					Leaks	
36					Moisture problems	
37					Condensation	
38					Combustion products	
39			Outdoor Section	Inlet/Outlet	Obstruction	
40				Condenser	Low Airflow	Fouling
41						Obstruction
42						Damaged Surfaces/Fins
43					Reduced heat transfer effectiveness (non-airflow)	Fouling
44						Damaged Surfaces/Fins
45				Condenser Fan	Variable Speed Drive	Improper Operation
46					Motor contactor	Pitting/other damage
47					Bearing	Wear
48					Belt	Wear
49						Improper Tension
50					Sheave	Wear
51						Improper Alignment
52					Fan blades	Dirty/damaged
53					Fan Housing	Dirty/damaged
54					Fan drive	Wear
55						Poor alignment
56						Poor bearing seating

Table 5 – Fault Failure Modes Analysis - 3

ID	Faults								
57	Air Conditioner / Heat Pump	Air-side Circuit	Economizer	Housing				Dirty/compromised integrity	
58				Filter				Dirty	
59				Sensor Faults	Digital Communicating	No communication or Error message	Outdoor sensor	Bad condition/setting/operation	
60					Sensor output does not change when conditions change				
61					Analog	Open or no signal	Return air sensor	Bad condition/setting/operation	
62					Sensor output does not change when conditions change		Mixed air/discharge sensor	Damaged	
63				Economizer controller	Inaccurate reading		Temperature, Humidity, Flow	Bad condition/setting/operation	
64					Changeover controller				Bad condition / setting / operation
65					High limit setpoint				
66					Low limit setpoint				
67					Range/action setup incorrect				
68					Minimum OA				
69				Dampers/Actuators			Outside air damper	Obstruction / stuck damper	
70								Dirty/no lubrication/damaged	
71							Return air damper	Obstruction / stuck damper	
72								Dirty/no lubrication/damaged	
73							Relief air damper	Obstruction / stuck damper	
74								Dirty/no lubrication/damaged	
75							Outside air damper motor	Damaged components	
76								No lubrication	
77								Bad setting	
78							Actuator / Linkage	Wear	Broken
79									Mis-aligned
80									Loose
81								No lubricant	
82				Symptoms				Air temperature sensor failure/fault	
83								Not economizing when it should	
84								Ecopnomizing when it should not	
85								Damper not modulating	
86								Excess outdoor air	
87								Low ventilation	
88				Disabled					

Table 6 – Fault Failure Modes Analysis - 4

ID	Faults					
89	Air Conditioner / Heat Pump	Air-side Circuit	Cabinet	Panels	Filter Panel	Missing
90						Damaged
91					Fan Access Panel	Missing
92						Damaged
93					Compressor Panel	Missing
94						Damaged
95				Fasteners	Missing	
96					Damaged	
97				Gaskets	Damaged	
98				Curbs	Damaged	
99			Ducts	Other symptoms	High pressure drop	
100				Improper install		
101				Obstruction / Restriction		
102				Air leaks		
103		Refrigerant-side Circuit	Refrigerant charge	High Charge	High Charge	
104					High Charge - Compromised Blend	
105				Low Charge	Low Charge	
106					Oil loss	
107					Low Charge - Compromised Blend	
108				Non-Condensables / Contaminants		
109			Refrigerant Circuit Lines	Liquid Line	Bend / Obstruction	
110					Refrigerant leaks	
111				Suction Line	Bend / Obstruction	
112					Refrigerant leaks	
113					Oil return	
114				Discharge Line	Bend / Obstruction	
115					Refrigerant leaks	
116				Evaporator circuit	Refrigerant leaks	
117				Condenser circuit	Refrigerant leaks	

Table 7 – Fault Failure Modes Analysis - 5

ID	Faults					
118	Air Conditioner / Heat Pump	Refrigerant-side Circuit	Compressor	Inefficient	Valve Leakage	
119					Missing pistons	
120					Excessive tolerance (scroll)	
121					Running backwards	
122				Locked rotor	Seized Bearing	
123				Oil	Low Oil level/pressure	
124				Variable Speed Drive	Improper Operation	
125				Motor failure	Open	Damaged motor
126						Thermal overload
127					Shorted with acid	Overheating
128					Shorted without acid	
129				Motor contactor	Pitting/other damage	
130				Other symptoms	Short cycling	
131			Expansion Device	Fixed metering - capillary tube	Restricted	
132					Restricted, undersized	
133					Overzized	
134				Fixed metering - piston	Installed backwards	
135					Restricted	
136					Restricted, undersized	
137					Overzized	
138				Fixed metering - short orifice	Restricted	
139				Thermostatic Expansion Valve (TXV)	Obstruction	
140					Sensing Bulb Fault - excessive heat absorption (not insulated, hanging, missing straps)	
141					Sensing Bulb Fault - lost charge (dead power	
142					Improper Adjustment - insufficient mass flow	
143					Improper Adjustment - excessive mass flow	
144				Electronic Expansion Valve (EEV)	Obstruction	
145					Sensor Fault	
146					Improper Adjustment - insufficient mass flow	
147					Improper Adjustment - excessive mass flow	
148			Filter/Drier	Obstruction		

Table 8 – Fault Failure Modes Analysis - 6

ID	Faults			
149	Air Conditioner / Heat Pump	Control system	Thermostat	Incorrect scheduling
150				Improper Programming/Adjustment
151				Improper Location
152				Communication Failure
153			Sensors	Failure/fault
154				Drift
155			Control Box	Dirt/debris
156				Loose terminations
157			Low ambient head pressure control	Damaged components
158				Software/algorithm modifications needed
159			Other devices?	Improper operation
160			Other symptoms	Improper operation
161		Misc.	Steam system traps, pumps, and controls	Dirty/broken
162			P-trap	Not primed
163			Other field-servicable bearings	Wear
164			Condensate drain pan	Biological growth
165			Condensate drain line	Biological growth
166				Obstruction
167			Exposed ductwork	Missing insulation
168			External piping	Missing insulation
169			Vapor barrier	compromised integrity
170			Insulation	Biological growth
171			Other areas	Moisture carryover beyond drain pan from evaporator condensate
172				Biological growth
173			Other symptoms	Efficiency does not meet unit rating
174				Capacity does not meet unit rating

Table 9 through Table 15 shows the language from various sources, interpreted to populate the previous fault hierarchy. In Table 9 through Table 12, key items are emphasized to help identify the particular fault being addressed.

Table 9 – Identifying Faults (Citation: ASHRAE Standard 180-2012 – RTUs)

TABLE 5-22 Rooftop Units		
	Inspection/Maintenance Task	**Frequency**
a	Check for **particulate accumulation** on **filters.** Clean or replace as necessary to ensure proper operation.	Quarterly
b	Check **ultraviolet lamp**. Clean or replace as needed to ensure **proper operation**.	Quarterly
c	Check **steam system traps**, **pumps,** and **controls.** Clean or replace as needed to **ensure proper operation**.	Semiannually
d	Check **control system** and devices for evidence of **improper operation**. Clean, lubricate, repair, adjust, or replace components as needed to ensure proper operation.	Semiannually
e	Check **P-trap**. Prime as needed to **ensure proper operation**.	Semiannually
f	Check **fan belt tension.** Check for belt **wear** and replace if necessary to ensure proper operation. Check **sheaves** for evidence of **improper alignment** or evidence of **wear** and correct as needed.	Semiannually
g	Check **variable-frequency drive** for **proper operation**. Correct as needed.	Semiannually
h	Check for evidence of **buildup or fouling** on **heat exchange surfaces**. Restore as needed to ensure proper operation.	Semiannually
i	Check for proper operation of **cooling coil**, **heating coil**, or **heat exchangers** and for **damage** or evidence of **leaks.** Clean, restore or replace as required.	Semiannually
j	Check **air filter fit** and **housing seal integrity**. Correct as needed.	Annually
k	Check **control box** for **dirt, debris, and/or loose terminations**. Clean and tighten as needed.	Annually
l	Check **motor contactor** for **pitting** or **other signs of damage**. Repair or replace as needed.	Annually
m	Check **fan blades** and **fan housing**. Clean, repair, or replace as needed to ensure proper operation.	Annually
n	Check refrigerant system temperatures. If **outside of recommended levels**, find cause, repair, and adjust **refrigerant charge** to achieve optimal operating levels.	Annually

Table 10 – Identifying Faults (Citation: ASHRAE Standard 180-2012 – RTUs continued)

TABLE 5-22 Rooftop Units (continued)		
	Inspection/Maintenance Task	**Frequency**
o	Check **fan drive** for **wear** or problems due to **poor alignment** or **poor bearing seating**. Repair or replace as needed.	Annually
p	Check **integrity** of all **panels** and **curbs** on equipment. Replace **fasteners** as needed to ensure proper integrity and fit/finish of equipment.	Annually
q	Assess **field-serviceable bearings**. **Lubricate** if necessary.	Annually
r	Check **drain pan**, **drain line**, and **coil** for **biological growth**. Clean as needed.	Annually
s	Check **evaporator coil fins**. Restore if possible. Replace coil if necessary to return to proper functioning.	Annually
t	Inspect for evidence of **moisture carryover beyond the drain pan** from cooling coils. Make corrections or repairs as necessary.	Annually
u	Check for proper **damper operation.** Clean, lubricate, repair, replace, or adjust as needed to ensure proper operation.	Annually
v	Inspect **air-cooled condenser surfaces** for **damage** or evidence of **leaks.** Repair or clean as needed.	Annually
w	Check **low ambient head pressure control sequence** for proper operation. Repair or replace components or modify software/algorithm to ensure proper operation.	Annually
x	Check **combustion chamber**, **burner,** and **flue** for **deterioration, leaks, moisture problems**, **condensation,** and **combustion products**. Clean, test, and adjust combustion process for proper operation.	Annually
y	Visually inspect **insulation** and **areas of moisture accumulation** for **biological growth.** If present, clean or disinfect as needed.	Annually
z	Check c**ompressor oil** levels and/or pressure on refrigerant systems having oil level and/or pressure measurement means. Repair, replace, or adjust as needed to ensure proper operation.	Annually
aa	Visually inspect **exposed ductwork** and **external piping** for **insulation** and **vapor barrier** for **integrity**. Correct as needed.	Annually

Table 11 – Identifying Faults (Citation: ASHRAE Standard 180-2012 – Furnaces)

TABLE 5-16 Furnaces, Combustion Unit Heaters		
	Inspection/Maintenance Task	**Frequency**
a	Visually inspect **fuel filter**. Clean, repair, or replace as needed to ensure proper operation.	Monthly
b	Check for **particulate accumulation** on **filters**. Clean or replace as necessary to ensure proper operation.	Quarterly
c	Check **fuel pump** for proper operation. Repair or replace as needed to ensure proper operation.	Semiannually
d	**Check control system and devices** for evidence of improper operation. Clean, lubricate, repair, adjust, or replace components as needed to ensure proper operation.	Semiannually
e	Check **fan belt** tension. Check for **belt wear** and replace if necessary to ensure proper operation. Check **sheaves** for evidence of **improper alignment** or evidence of **wear** and correct as needed.	Semiannually
f	Check **air filter fit** and **housing seal integrity.** Correct as needed.	Annually
g	Check **control box** for **dirt, debris,** and/or **loose terminations**. Clean and tighten as needed.	Annually
h	Check **fan blades** and **fan housing**. Clean, repair, or replace as needed to ensure proper operation. Annually	Annually
i	Check **fan drive** for problems due to **poor alignment** or **poor bearing seating**. Repair or replace as needed.	Annually
j	Check **integrity** of **all panels** on equipment. Replace **fasteners** as needed to ensure proper **integrity** and **fit/finish** of equipment.	Annually
k	Assess field-serviceable **bearings.** Lubricate if necessary.	Annually
l	Check for proper damper operation. Clean, lubricate, repair, replace, or adjust as needed to ensure proper operation. Annually	Annually
m	Check **heat exchanger**, **combustion chamber**, **burner,** and **flue** for **deterioration, moisture problems**, **condensation,** and **combustion products**. Clean, test, and adjust combustion process for proper operation.	Annually
n	Verify proper operation of **safety devices** per manufacturer's recommendations. Repair or replace as needed. Annually	Annually
o	Check for proper operation of **heating coil** and for **damage** or evidence of **leaks.** Clean, restore, or replace as required. Annually	Annually

Table 12 – Identifying Faults (Citation: ASHRAE Standard 180-2012 – Air-side economizers)

TABLE 5-12 Economizers—Air-Side		
	Inspection/Maintenance Task	
a	Check **air filter** and **housing integrity.** Correct as needed.	Monthly
b	Check for **particulate accumulation** on **filters.** Clean or replace as necessary to ensure proper operation.	Monthly
c	Check **condition, setting, and operation** of **outdoor sensor**, **return air sensor**, or **change-over controller**. Repair, adjust, or replace components to ensure proper operation.	Semiannually
d	Check **condition, setting, and operation** of the **economizer controller**. Repair, adjust, or replace components to ensure proper operation.	Semiannually
e	Check **condition, setting, and operation** of the **mixed-air/discharge sensor** or **changeover controller**. Repair, adjust, or replace components to ensure proper operation.	Semiannually
f	Check **dampers** for **proper condition, setting, and operation**. Repair, adjust, lubricate, or replace components to ensure proper operation.	Semiannually
g	Check **condition, setting, and operation** of the **economizer damper motors**. Repair, adjust, lubricate, or replace components to ensure proper operation.	Semiannually
h	Check sealing integrity of **all panels on equipment**. Replace **fasteners and gasketing** as needed.	Semiannually
i	Visually inspect areas of moisture accumulation for **biological growth**. If present, clean or disinfect as needed.	Semiannually
j	Assess **field-serviceable bearings**, lubricate if necessary.	Annually
k	Check **condition, setting, and operation** of the **low-limit stat**. Repair, adjust, or replace components to ensure proper operation.	Annually

Table 13 – Identifying Faults from the WCEC Contractor Survey

RTU Faults Found More than 20% of the Time		
2013 Survey of 25 Contractors/Technicians – WCEC		
1	Condensate	Condensate leaks - drain line plugged
2	Condenser Coil	Dirty coil affecting heat transfer efficiency but not airflow
3	Condenser Coil	Dirty coil affecting airflow
4	Controls	Schedule not matching occupancy
5	Controls	Thermostat programmed incorrectly: fan cycles with AC
6	Ducts	Improper installation
7	Ducts	Leaky ducts
8	Ducts	High duct pressure drop
9	Ducts	Restrictive return duct, resulting in low airflow and high static pressure
10	Economizer	Economizer is disabled and dampers are closed
11	Economizer	Actuator/linkage broken, misaligned, or loose, due to normal wear and tear or lack of lubrication
12	Economizer	High/low limit setpoints incorrect, set by installing contractor
13	Economizer	Range/action setup incorrectly
14	Economizer	Min Outside Air is not set correctly: too low
15	Evaporator Coil	Fouled coil
16	Fan Motor	Worn belts
17	Fan Motor	Belt too loose
18	Filters	Dirty Filter
19	Supply Fan	Dirty blower

Table 14 – Identifying Faults from the DOE RTU Challenge Specifications

DOE High Performance Rooftop Unit Challenge
18. Enable the DDC unit controller’s automated self-check sequence to provide the following diagnostic checks as a start-up commissioning function:
a. Low Evaporator Air Flow
b. High Refrigerant Charge
c. Low Refrigerant Charge
d. Sensor Failure/Fault (including drifting out of calibration) RTU Long V1.2 26
e. Equipment Short Cycling
f. Dirty Filter
g. Efficiency does not meet unit rating
h. Capacity does not meet unit rating
i. Economizer Faults
1) Damper not modulating (stuck damper)
2) Not economizing when it should
3) Excess outdoor air
4) Low ventilation

Table 15 – Identifying Faults from Title 24 Economizer FDD Mandatory Requirements

SECTION 120.2 – REQUIRED CONTROLS FOR SPACE-CONDITIONING SYSTEMS
(i) Economizer Fault Detection and Diagnostics (FDD)…
7. The FDD system shall detect the following faults:
A. Air temperature sensor failure/fault;
B. Not economizing when it should;
C. Economizing when it should not;
D. Damper not modulating;
E. Excess outdoor air.

The 2016 Title 24 Building Energy Efficiency Standards (Title 24) detail mandatory requirements for FDD capabilities[5] (see SUBCHAPTER 3 NONRESIDENTIAL, HIGH-RISE RESIDENTIAL, HOTEL/MOTEL OCCUPANCIES, AND COVERED PROCESSES—MANDATORY REQUIREMENTS, SECTION 120.2 – REQUIRED CONTROLS FOR SPACE-CONDITIONING SYSTEMS, (i) Economizer Fault Detection and Diagnostics). All HVAC systems that are "Air-cooled unitary direct expansion units include packaged, split systems, heat pumps, and variable refrigerant flow (VRF), where the VRF capacity is defined by that of the condensing unit…" are required to have FDD capability to detect/diagnose faults centric to air-side economizers.

[5] http://www.energy.ca.gov/Title24/2013standards/index.html

Table 16 through Table 19 illustrates the various FDD technologies that are commercially available at the time of this report.

Table 16 – FDD Technologies List – 1 - 30

#	Manufacturer	Product	Model	T-24 Certified?
1	AAON Inc	VCMX RNE Controller - AAON Tulsa	V17110	Yes
2	AAON Inc	VCMX Modular - With Ebus-AAON Tulsa	V07150	Yes
3	AAON Inc	VCMX-Water Source Heat Pump - AAON Tulsa	V07140	Yes
4	AAON Inc	VCMX SA With Ebus controller - AAON Tulsa	V07160	Yes
5	AAON Inc	VCMX-Modular for AAON Coil	31422	Yes
6	AAON Inc	VCMX-Water Source Heat Pump for AAON Coil	31423	Yes
7	AAON Inc	VCMX for UPS - AAON Tulsa	V0715U	Yes
8	AAON Inc	VCBX Controller - AAON Tulsa	V28940	Yes
9	AAON Inc	VCBX Controller - AAON Coil	J00142	Yes
10	AAON Inc	VCBX Controller - AAON	V2894K	Yes
11	Alerton, L&H Airco	Alerton/Ascent	VLC-651R, VLC-853, VLC-1188, VLCA-1688, VLD-362, VLD-362W, VLXP w/EXP	Yes
12	Alerton, L&H Airco	Alerton/BACtalk	VLC-651R, VLC-853, VLC-1188, VLCA-1688, VLD-362, VLD-362W, VLXP w/EXP	Yes
13	Alerton, L&H Airco	Alerton Visual Logic	VLD-362, VLD-362W	Yes
14	Bard Manufacturing	Bard-Link Controller	LC1000-100 Series	Yes
15	Bard Manufacturing	Bard-Link Controller	LC1500-100 Series	Yes
16	Belimo	ZIP Economizer	ECON-ZIP-BASE	Yes
17	Bryant	OPN-RTUM2 (RTU-Open)	HK50AL002	Yes
18	Carrier	Comfortlink WeatherMaster	50HE502669	Yes
19	Carrier	Comfortlink WeatherExpert	48HC500132	Yes
20	Carrier	Comfortlink A Series VAV	48EJ503222	Yes
21	Carrier	Comfortlink A Series CV	48EJ503465	Yes
22	Carrier	Comfortlink P Series	48ZZ502884	Yes
23	Carrier	Comfortlink N Series	48NG500468	Yes
24	Carrier	OPN-RTUM2	HK50AL002	Yes
25	Carrier	I/O Flex (Target)	48TM504657	Yes
26	Carrier	I/O Flex (7-11)	48TM505032	Yes
27	Carrier	SystemVu (48/50 LC WeatherExpert)	50LC500924	Yes
28	Carrier	Infinity Control		
29	Carrier	PremierLink Controller		
30	Cimetrics	Analytika (formerly Infometrics)		

Table 17 – FDD Technologies List – 31 - 60

#	Manufacturer	Product	Model	T-24 Certified?
31	ClimaCheck	ClimaCheck Online		
32	ClimaCheck	PA Pro II Fixed		
33	ClimaCheck	PA Pro II Portable		
34	ClimaCheck	Performance Analyzer		
35	ClimaCheck	Systems Analysis Expertise		
36	Conservation Services Group	Energy Measure HVAC		
37	Daikin	DDC Controller	PCBCG100	Yes
38	Daikin Applied Americas Inc.	RoofPak	RPS 15-140D	Yes
39	Daikin Applied Americas Inc.	RoofPak	RDT 45-140D	Yes
40	Daikin Applied Americas Inc.	RoofPak	RPE 76-150C	Yes
41	Daikin Applied Americas Inc.	RoofPak	RDE 76-150C	Yes
42	Daikin Applied Americas Inc.	RoofPak	RDS 800-802C	Yes
43	Daikin Applied Americas Inc.	RoofPak	RAH 47-77C	Yes
44	Daikin Applied Americas Inc.	Maverick II	MPS 17F	Yes
45	Daikin Applied Americas Inc.	Maverick II	MPS 20-26G	Yes
46	Daikin Applied Americas Inc.	Maverick II	MPS 30-50F	Yes
47	Daikin Applied Americas Inc.	Maverick II	MPS 15-17F	Yes
48	Daikin Applied Americas Inc.	Maverick II	MPS 20-26G	Yes
49	Daikin Applied Americas Inc.	Maverick II	MPS 30-75F	Yes
50	Daikin Applied Americas Inc.	Rebel	DPS 3-15	Yes
51	Daikin Applied Americas Inc.	Rebel	DPS 3-28A	Yes
52	Detechtion Technologies	Enalysis		
53	Emerson Climate Technologies	Comfort Encoded™ Solutions - Thermostats		
54	Emerson Climate Technologies	ComfortGuard™ mobile application		
55	Emerson Climate Technologies	CoreSense™		
56	Ezenics (Formerly Sensus MI)	Automated Continuous Commissioning™		
57	Ezenics (Formerly Sensus MI)	Optimized Operational Readiness™ - Automated Fault Detection Diagnostics and Impact (AFDDI™)		
58	Facility Dynamics Engineering	Performance and Continuous Re-Commissioning Analysis Tool (PACRAT)		
59	Facility Solutions Group, (FSG)	Clarity EMS™		
60	Field Diagnostics Services Inc	Building Performance Analytics/Center of Excellence		

Table 18 – FDD Technologies List – 61 - 90

#	Manufacturer	Product	Model	T-24 Certified?
61	Field Diagnostics Services Inc	HVAC Service Assistant		
62	Field Diagnostics Services Inc	SAMobile		
63	Fieldpiece	HVAC Guide® System Analyzer, model HG2 (Retired)		
64	Fieldpiece	HVAC Guide® System Analyzer, model HG3		
65	Greenheck Fan Corporation	TAP v2.3	RV	Yes
66	Greenheck Fan Corporation	TAP v2.3	RVE	Yes
67	Honeywell	Jade	W7220A10XX	Yes
68	Honeywell	Jade	W7220A	Yes
69	Imperial	iManifold		
70	Johnson Controls	RRS Advanced Econonimizer Controller	RK-ECO1011-0	Yes
71	Johnson Controls	Simplicity SE Unit Controller	SE-SPU1001-0/SE-ECO1001-0	Yes
72	Johnson Controls	Simplicity SE Unit Controller	SE-SPU1002-0/SE-ECO1001-0	Yes
73	Johnson Controls	Simplicity SE Unit Controller	SE-SPU1011-0/SE-ECO1001-0	Yes
74	Johnson Controls	Simplicity SE Unit Controller	SE-SPU1012-0/SE-ECO1001-0	Yes
75	Johnson Controls	IPU Unit Controller	YPAL50-150 Series 100	Yes
76	KGS Buildings	Clockworks		
77	Lennox	iComfort		
78	Lennox	Prodigy Control System	102458/102542	Yes
79	Lennox	Prodigy 2.0 Control System	103956	Yes
80	Lennox	SmartAirflow™		
81	MasterCool	A/C System Analyzer		
82	MyEnergy Domain, Inc	MyEnergy PerformanceTM MyEnergy AdviceTM MyEnergy SmartHomeTM MyEnergy StoreTM MyEnergy AggregationTM MyEnergy ForumTM MyEnergy SearchTM		
83	Nordyne	iQ Drive System Thermostat Controller Kit		
84	NorthWrite	Energy Expert		
85	Pacific NorthWest National Laboratory	Smart Monitoring and Diagnostic Systems (SMDS)		
86	Pelican Wireless Systems	PEARL	PEARL	Yes
87	Proctor Engineering Group	CheckMe!®		
88	SCIEnergy	SCIwatch		
89	Seasons 4	OEMCtrl	IOPro812U	Yes
90	Sporlan	SMART Service Tool Kit		

Table 19 – FDD Technologies List – 91 - 118

#	Manufacturer	Product	Model	T-24 Certified?
91	Testo	550 or 557 Digital Manifold		
92	Testo	Refrigeration App		
93	Trane	Comfort Link II		
94	Trane	Packaged IntelliPak™ Rooftop Systems (IPAK I, IPAK II)		
95	Trane	ReliaTel (precedent, Voyager II, Voyager III)		
96	Transformative Wave	CATALYST	CAT-371-T24	Yes
97	Transformative Wave	eIQ Platform		
98	UTOnline.org	Universal Translator		
99	VirtJoule	Expert-To-Expert Service		
100	VirtJoule	Standard Monitoring Service		
101	WattMaster Controls Inc	DDC Controller	OE377-26B-00001	Yes
102	WattMaster Controls Inc	VCMX RNE Controller - AAON Tulsa	OE332-23E-RNE-A	Yes
103	WattMaster Controls Inc	VCMX Modular - With Ebus-AAON Tulsa	OE332-23E-VCMX-MOD-A	Yes
104	WattMaster Controls Inc	VCMX-Water Source Heat Pump - AAON Tulsa	OE332-23E-VCMX-WSHP-A	Yes
105	WattMaster Controls Inc	VCMX SA With Ebus controller - AAON Tulsa	OE332-23E-VCMX-SA-A	Yes
106	WattMaster Controls Inc	VCMX-Modular for AAON Coil	OE332-23E-VCMX-MOD-C	Yes
107	WattMaster Controls Inc	VCMX-Water Source Heat Pump for AAON Coil	OE332-23E-VCMX-WSHP-C	Yes
108	WattMaster Controls Inc	VCMX for UPS - AAON Tulsa	OE332-23E-UPS	Yes
109	WattMaster Controls Inc	VCBX Controller - Orion	OE335-26B-VCBX	Yes
110	WattMaster Controls Inc	VCBX Controller - AAON Tulsa	OE335-26B-VCBX-A	Yes
111	WattMaster Controls Inc	VCBX Controller - AAON Coil - Longview	OE335-26B-VCBX-C	Yes
112	WattMaster Controls Inc	VCBX Controller - AAON Tulsa	OE335-26B-VCBX-AK	Yes
113	WattMaster Controls Inc	VCC-X Controller -Orion	OE338-26B-VCCX	Yes
114	WattMaster Controls Inc	VCC-X Controller - AAON Tulsa	OE338-26B-VCCX-A	Yes
115	WattMaster Controls Inc	VCC-X Controller - AAON Tulsa	V42430	Yes
116	XCSpec, LLC	EconomizerPro Montoring System	EconomizerPro Kit	Yes
117	Yellow Jacket	MANTOOTH™ DUAL PRESSURE WIRELESS DIGITAL P/T GAUGE		
118	York	Simplicity® Smart Equipment controls - Optional Insight™ FDD		

There is much uncertainty surrounding the wide ranging capabilities of the FDD technologies listed. More should be done to have industry-established classifications of FDD, to better understand their different roles and functions. Such classifications are done in the HVAC industry with respect to other equipment, such as split systems, packaged rooftop units, portable terminal air conditioners, etc. Table 20 lists terminology considerations for classifying FDD technologies, based on general conversations with industry professionals, through venues such as ASHRAE, or the WHPA FDD committee.

Table 20 – FDD Technology Terms / Classifications

Terms	Definition
1. In-Field	FDD technologies that use portable equipment that is deployed on the spot or left on site for a limited amount of time
a. FDD Hand Tools	See in-field
b. Short-term retrofit	See in-field
2. Onboard	FDD technologies that use permanently installed sensors to provide monitored data to an onboard data processor, to a computer that is permanently installed, or to a communications gateway that provides data to a site off the roof, either in the building or to a remote location across town or even across the country
a. Integrated	See onboard
b. Factory-Installed	Devices or FDD capabilities that are permanently installed on HVAC systems as options supplied by the HVAC manufacturer
c. Long-term Retrofit / 3rd Party	Automated devices or FDD capabilities that are permanently installed on HVAC systems by a 3rd party.
d. Software	Analytic software or algorithm that incorporates automated FDD capabilities, that may or may not include its own sensors or hardware. It may leverage information from building energy management systems or from other available monitored sensors or data sources.
e. Thermostat	A thermostat that has onboard FDD capability
3. Custom Service	FDD offered as a service that leverages automated technologies such as FDD software, in-field FDD technologies, and/or onboard FDD technologies.

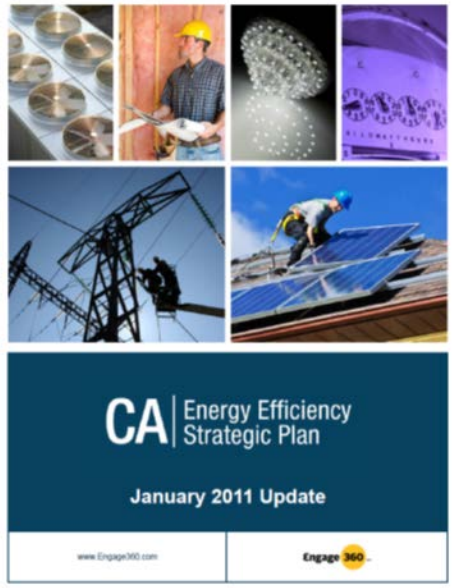
The California Long Term Energy Efficiency Strategic Plan specifically identifies diagnostics as part of its goals & strategies.

> "On Sept. 18, 2008, the CPUC adopted California's first Long Term Energy Efficiency Strategic Plan, presenting a single roadmap to achieve maximum energy savings across all major groups and sectors in California. The Strategic Plan was subsequently updated in January 2011 to include a lighting chapter.
>
> This comprehensive Plan for 2009 to 2020 is the state's first integrated framework of goals and strategies for saving energy, covering government, utility, and private sector actions, and holds energy efficiency to its role as the highest priority resource in meeting California's energy needs."[6]
>
> "6. Heating, Ventilation and Air Conditioning
>
> …
>
> Goal 4: New climate-appropriate HVAC technologies (equipment and controls, including system diagnostics) are developed with accelerated marketplace penetration.
>
> The strategies to achieve this goal include:
>
> Commercialize on-board diagnostic systems: Such systems automatically collect data and alert consumers and/or contractors when a fault or negative performance trend is detected. These diagnostics will result in energy benefits by helping ensure that HVAC systems are maintained and operate within design specifications. While many manufacturers currently offer either ―on-board systems or hand-held ones that work with all systems, none are widely used by consumers or contractors. Actions to accelerate the commercialization of such diagnostics include:
>
> Prioritizing in-field diagnostic and maintenance approaches based on the anticipated size of savings, cost of repairs, and the frequency of faults occurring.
>
> Benchmarking of existing diagnostic, repair, and maintenance protocols.
>
> Developing nationwide standards and/or guidelines for onboard diagnostic functionality and specifications for designated sensor mount locations.

Aggressive promotion of diagnostic systems as a standard offering on all HVAC equipment."

[6] http://www.cpuc.ca.gov/General.aspx?id=4125

Figure 6 – The California Long-Term Energy-Efficiency Strategic Plan[6]



Test Methodology

Steady-State Heating and Cooling Performance Tests

The majority of tests were conducted at controlled conditions, in a manner guided by the standards set forth by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) and the Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American National Standards (ANSI). The applicable standards are:

1. ANSI/ASHRAE Standard 37-2009 Method of testing for rating unitary air-conditioning and heat pump equipment
2. AHRI Standard 210/240, 2008 version: Performance rating of unitary air-conditioning & air-source heat pump equipment

These tests leveraged controlled environmental chambers in steady-state, non-cycling performance tests. Each test consisted of two distinct periods: a steady-state period and a measurement period. During the steady-state period, the unit operated at the specified test chamber conditions for a minimum of 30 minutes. Then, the unit continued to operate under the same conditions for an additional 30 minutes, where measurements were made and averaged. Reported parameters shall be the averages across the 30 minute measurement window.

Economizer FDD Tests

Economizer FDD tests were conducted with guidance from the 2016 Title 24 Building Energy Efficiency Standards (Title 24) Economizer FDD sample test procedures[7]. These tests did not require the use of controlled environmental chambers. General lab space conditioning provided fairly stable ambient temperatures of roughly 76°F, sufficient to run economizer fault testing.

[7]Joint Appendices, JA6.3.3, table 2. http://www.energy.ca.gov/Title24/2016standards/index.html

Test Equipment

Figure 7 – Test RTU

The test RTU chosen is a standard efficiency heat pump. Table 21 lists various specifications of the test RTU.

Table 21 – Test RTU Specifications

Type	RTU, Heat Pump
Voltage	208-230, 1-Phase
ID Fan	Direct Drive, ECM, Constant Torque
Nameplate Charge	10 lbs
Refrigerant	R-410a
Expansion Device	TXV
Gross Cooling Capacity	63,440 Btu/hr
SEER	13
Nominal AHRI Rated ID CFM	2,000
AHRI Net Cooling Capacity	62,000 Btu/hr
System Power	5.13 kW
High Temp Rating (Heating)	58,500 Btu/hr
System kW/COP	4.94/3.50
Low Temp Rating (Heating)	34,400 Btu/hr
System kW/COP	4.44/2.30
HSPF	8
Compressor	Single Scroll

The FDD test equipment chosen were a mixture of in-field and onboard devices. Additionally, the outputs of the RTU charge protocol were examined.

1. FDD Unit 1 (in-field)
    a. Handheld device, wireless sensor hub

b. Digital refrigerant manifold, wireless communication
c. Two air temperature/humidity sensors, wireless communication
d. Clamp ammeter, wireless communication
e. Ambient temperature sensor, wireless communication

2. FDD Unit 2 (in-field)
    a. Phone/tablet app
3. FDD Unit 3 (in-field)
    a. Phone/tablet app
4. FDD Unit 4 (onboard)
    a. 3rd party design, economizer FDD (Title 24 certified)
5. RTU charging protocol

FDD units 1 through 3 were given their required inputs from laboratory average measurements.

Test Setup

Figure 8 through Figure 10 illustrate the measurement state points on the air-side and refrigerant-side circuits, respectively. The test setup uses a two-chamber configuration for the indoor (ID) and outdoor (OD) areas. The air-side state points A2 and A3 were sealed for the purposes of this testing. Table 22 through Table 26 summarizes all the laboratory measurement points. The addition of piping and the refrigerant mass flow meter increased the refrigerant charge of the system. The RTU charge protocol was followed, and the total charge increased to a total of 11 pounds (from the original 10 pounds). Manufacturer vacuum specifications were followed prior to establishing charge levels.

Figure 8. Air-side State Points

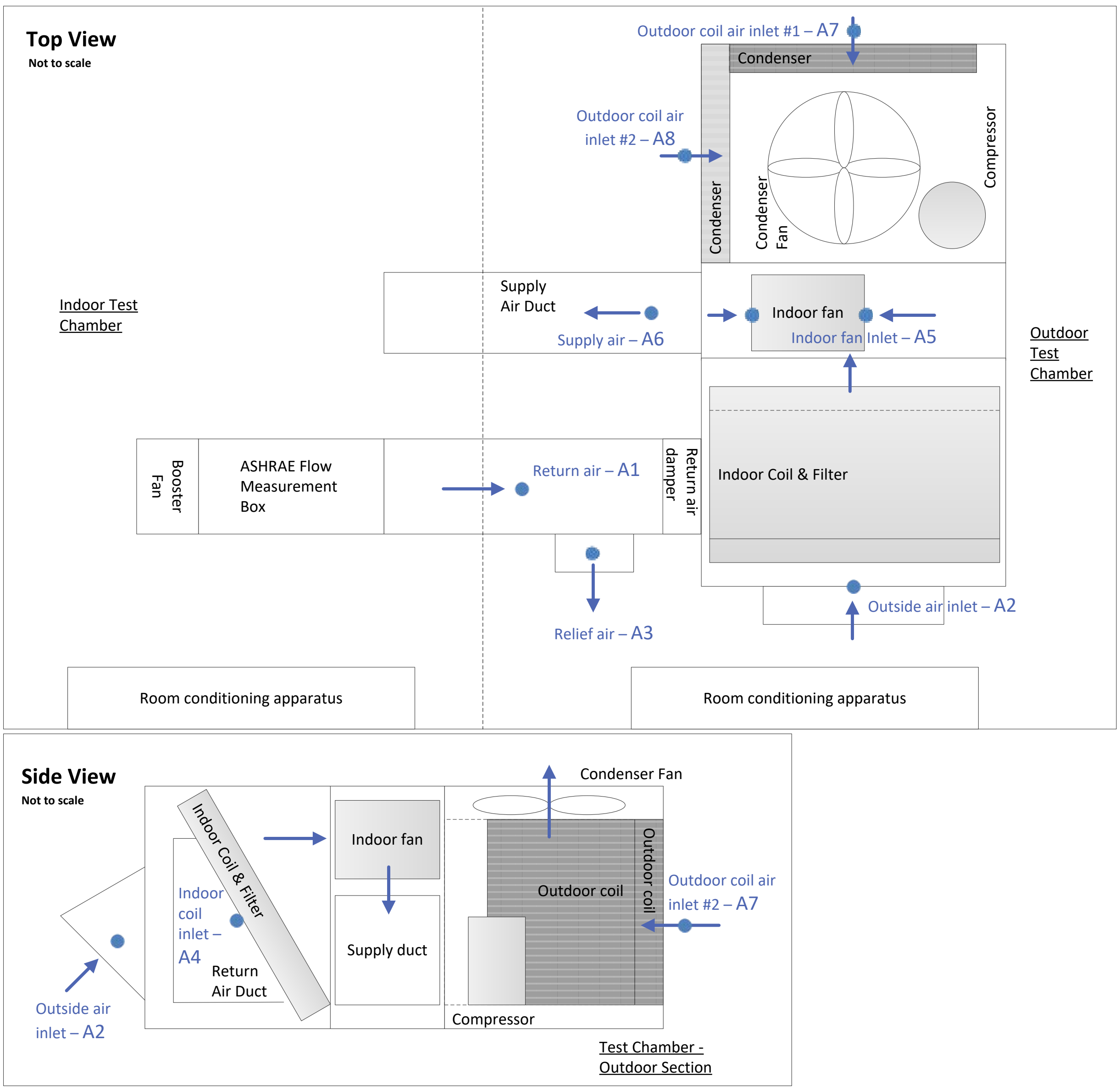


Figure 9. Air-side State Points: Cross-sections

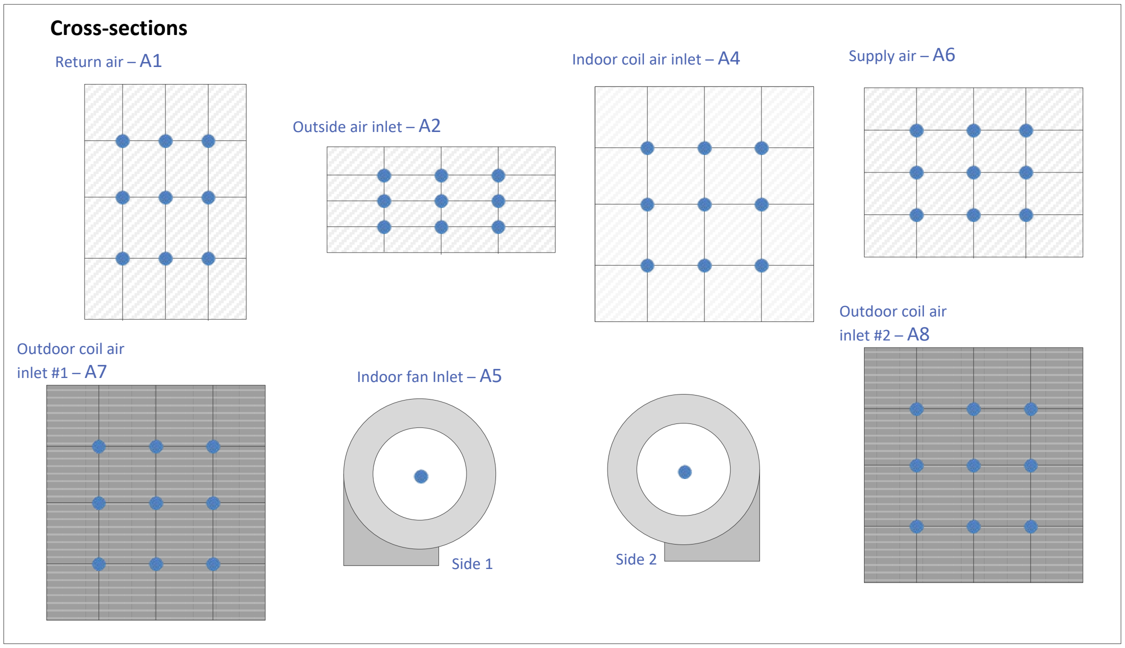


Figure 10. Refrigerant-side state points

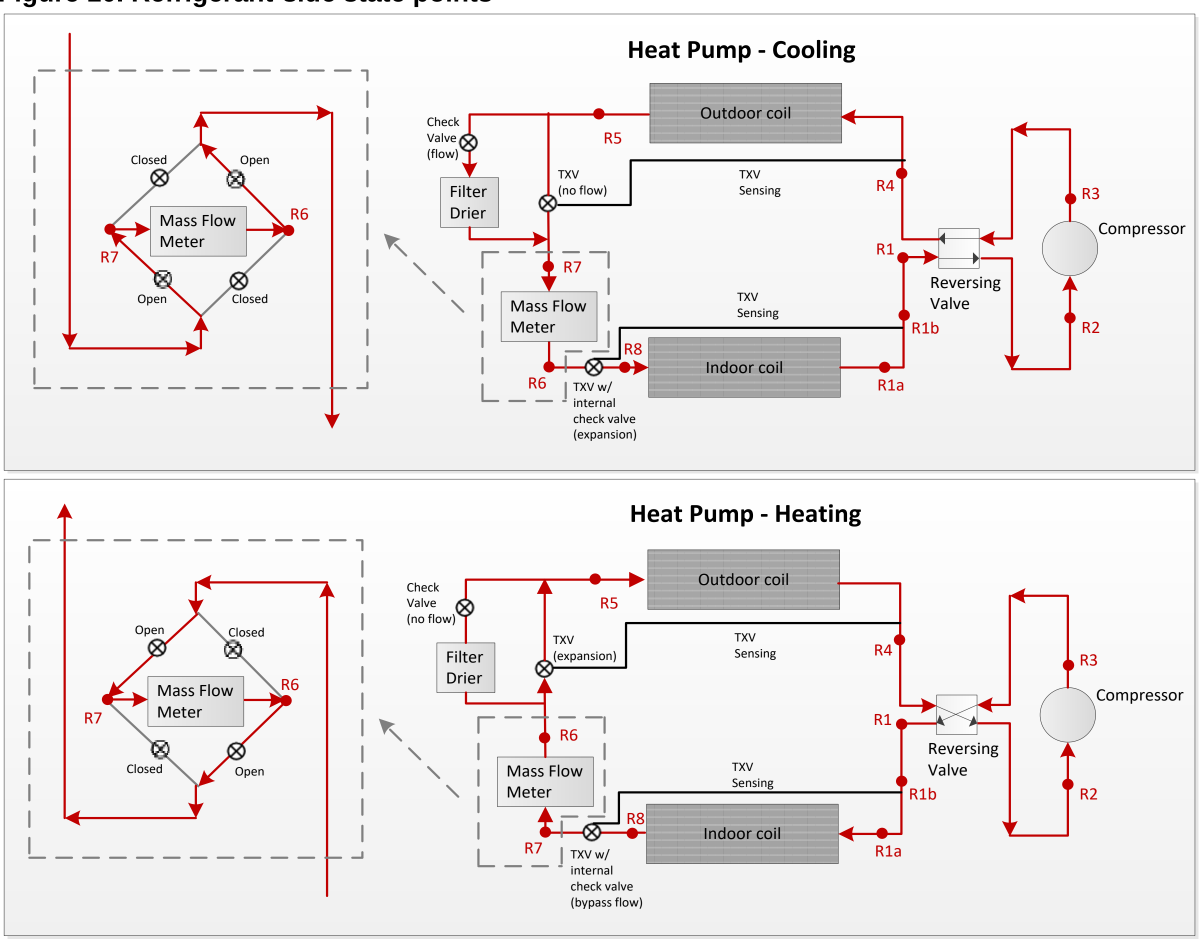


Table 22 – Sensor List: Refrigerant-side

Sensor #	Description	Units	Side?
1	R1a - refrigerant temperature - 6" from ID coil outlet	F	Refrigerant-side
2	R1b - refrigerant temperature - 1' from ID coil outlet	F	
3	R1 - refrigerant temperature	F	
4	R1 - refrigerant pressure	psig	
5	R2 - refrigerant temperature	F	
6	R2 - refrigerant pressure	psig	
7	R3 - refrigerant temperature	F	
8	R3 - refrigerant pressure	psig	
9	R4 - refrigerant temperature	F	
10	R4 - refrigerant pressure	psig	
11	R5 - refrigerant temperature	F	
12	R5 - refrigerant pressure	psig	
13	R6 - refrigerant temperature	F	
14	R6 - refrigerant pressure	psig	
15	R7 - refrigerant temperature	F	
16	R7 - refrigerant pressure	psig	
17	Refrigerant mass flow	lb/min	

Table 23 – Sensor List: Air-side, A1 & A2

Sensor #	Description	Units	Side?
18	A1 - Return air - DB temperature #1	F	Air-side
19	A1 - Return air - DB temperature #2	F	
20	A1 - Return air - DB temperature #3	F	
21	A1 - Return air - DB temperature #4	F	
22	A1 - Return air - DB temperature #5	F	
23	A1 - Return air - DB temperature #6	F	
24	A1 - Return air - DB temperature #7	F	
25	A1 - Return air - DB temperature #8	F	
26	A1 - Return air - DB temperature #9	F	
27	A1 - Return air - WB temperature (upstream of DB grid)	F	
28	A2 - Outside air inlet - DB temperature #1	F	
29	A2 - Outside air inlet - DB temperature #2	F	
30	A2 - Outside air inlet - DB temperature #3	F	
31	A2 - Outside air inlet - DB temperature #4	F	
32	A2 - Outside air inlet - DB temperature #5	F	
33	A2 - Outside air inlet - DB temperature #6	F	

34	A2 - Outside air inlet - DB temperature #7	F	
35	A2 - Outside air inlet - DB temperature #8	F	
36	A2 - Outside air inlet - DB temperature #9	F	
37	A2 - Outside air inlet - WB temperature (upstream of DB grid)	F	

Table 24 – Sensor List: Air-side, A4-A6

Sensor #	Description	Units	Side?
38	A4 - Indoor coil inlet air - DB temperature #1	F	Air-side
39	A4 - Indoor coil inlet air - DB temperature #2	F	
40	A4 - Indoor coil inlet air - DB temperature #3	F	
41	A4 - Indoor coil inlet air - DB temperature #4	F	
42	A4 - Indoor coil inlet air - DB temperature #5	F	
43	A4 - Indoor coil inlet air - DB temperature #6	F	
44	A4 - Indoor coil inlet air - DB temperature #7	F	
45	A4 - Indoor coil inlet air - DB temperature #8	F	
46	A4 - Indoor coil inlet air - DB temperature #9	F	
47	A4 - Indoor coil inlet air - WB temperature (upstream of DB grid)	F	
48	A5 - Indoor fan inlet air - DB temperature #1 (North)	F	
49	A5 - Indoor fan inlet air - DB temperature #2 (South)	F	
50	A5 - Indoor fan inlet air - WB temperature (upstream of DB grid)	F	
51	A6 - Supply air - DB temperature #1	F	
52	A6 - Supply air - DB temperature #2	F	
53	A6 - Supply air - DB temperature #3	F	
54	A6 - Supply air - DB temperature #4	F	
55	A6 - Supply air - DB temperature #5	F	
56	A6 - Supply air - DB temperature #6	F	
57	A6 - Supply air - DB temperature #7	F	
58	A6 - Supply air - DB temperature #8	F	
59	A6 - Supply air - DB temperature #9	F	
60	A6 - Supply air - WB temperature (upstream of DB grid)	F	

Table 25 – Sensor List: Air-side, A7 & A8

Sensor #	Description	Units	Side?
61	A7 - Outdoor coil air inlet #1 - DB temperature #1	F	Air-side
62	A7 - Outdoor coil air inlet #1 - DB temperature #2	F	
63	A7 - Outdoor coil air inlet #1 - DB temperature #3	F	
64	A7 - Outdoor coil air inlet #1 - DB temperature #4	F	

65	A7 - Outdoor coil air inlet #1 - DB temperature #5	F	
66	A7 - Outdoor coil air inlet #1 - DB temperature #6	F	
67	A7 - Outdoor coil air inlet #1 - DB temperature #7	F	
68	A7 - Outdoor coil air inlet #1 - DB temperature #8	F	
69	A7 - Outdoor coil air inlet #1 - DB temperature #9	F	
70	A8 - Outdoor coil air inlet #2 - DB temperature #1	F	
71	A8 - Outdoor coil air inlet #2 - DB temperature #2	F	
72	A8 - Outdoor coil air inlet #2 - DB temperature #3	F	
73	A8 - Outdoor coil air inlet #2 - DB temperature #4	F	
74	A8 - Outdoor coil air inlet #2 - DB temperature #5	F	
75	A8 - Outdoor coil air inlet #2 - DB temperature #6	F	
76	A8 - Outdoor coil air inlet #2 - DB temperature #7	F	
77	A8 - Outdoor coil air inlet #2 - DB temperature #8	F	
78	A8 - Outdoor coil air inlet #2 - DB temperature #9	F	
79	A8 - Outdoor coil air inlet #2 - WB temperature (upstream of DB grid)	F	

Table 26 – Sensor List: Air-side misc. & Electrical

Sensor #	Description	Units	Side?
80	Air static pressure taps across RTU **(downstream of DB grids) Supply 1**	in/wc	Air-side
81	Air static pressure taps across RTU **(downstream of DB grids) Return 1**	in/wc	
82	Air static pressure taps across RTU **(downstream of DB grids) Supply 2**	in/wc	
83	Air static pressure taps across RTU **(downstream of DB grids) Return 2**	in/wc	
84	Condensate mass	lbs	
85	Room 2 pressure	in WC	
86	ASHRAE airflow measurement device nozzle Delta-P #1	in WC	
87	ASHRAE airflow measurement device nozzle Delta-P #2	in WC	
88	Total RTU power	Watts	Electrical
89	Total RTU voltage	Volts	
90	Total RTU amperage	Amps	
91	Total RTU Frequency	Hz	
92	Compressor power	Watts	
93	Indoor coil fan power	Watts	
94	Outdoor coil fan power	Watts	

Calculations: Attempts were made to leverage as many calculation techniques as possible for cooling and heating capacity calculations. Equations for cooling generally took one of the following forms, with various established conversion factors/constants[8]:

$$\dot{Q}_{gross-cool\,(ref)} = \dot{m} \times \Delta h_{ID\ coil\,(ref)}$$

$$\dot{Q}_{gross-cool\,(ref)} = \dot{m} \times \left(\Delta h_{OD\ coil\,(ref)} - \Delta h_{comp\,(ref)}\right)$$

$$\dot{Q}_{gross-cool\,(ref)} = \dot{m} \times \Delta h_{OD\ coil\,(ref)} - C1 \times P_{comp}$$

$$\dot{Q}_{gross-cool\,(air)} = \dot{\forall} \times \rho \times \Delta h_{ID\ coil\,(air)} + C1 \times P_{ID\ Fan}$$

$$\dot{Q}_{gross-cool\,(air)} = \dot{Q}_{sensible} + \dot{Q}_{latent} + C1 \times P_{ID\ Fan}$$

$$\dot{Q}_{sensible} = \dot{\forall} \times \rho \times C_p \times \Delta T$$

$$\dot{Q}_{latent} = \dot{\forall} \times \rho \times C_p \times \Delta W$$

$$\dot{Q}_{latent} = \dot{m}_{scale} \times h_{vap,water}$$

Where

$\dot{Q}_{gross-cool\,(ref)}$ = Gross cooling capacity, refrigerant-side calculation, Btu/h

$\dot{m}$ = Refrigerant mass flow rate, lb/h

$\Delta h_{ID\ coil\,(ref)}$= Refrigerant-side enthalpy change between R1/R1a and R8, Btu/lb

$\Delta h_{OD\ coil\,(ref)}$= Refrigerant-side enthalpy change between R4 and R5, Btu/lb

$\Delta h_{comp\,(ref)}$= Refrigerant-side enthalpy change between R2 and R3, Btu/lb

$C1$ = Conversion factor, 3.413, Btu/h per Watt

P_{comp}= Electrical power measured at the compressor, Watts

$\dot{Q}_{gross-cool\,(air)}$ = Gross cooling capacity, air-side calculation, Btu/h

$\dot{\forall}$ = ID air volumetric flowrate, SCFM

ρ = Density of standard air, 0.0765 lbm/ft^3

$\Delta h_{ID\ coil\,(air)}$= Air-side enthalpy change between A1/A4 and A6, Btu/lb

$P_{ID\ Fan}$ = Electrical power measured at ID fan, Watts

$\dot{Q}_{sensible}$= Sensible cooling capacity, air-side calculation, Btu/h

$\dot{Q}_{latent}$= Latent cooling capacity, air-side calculation, Btu/h

[8] http://home.anadolu.edu.tr/~mcavcar/common/ISAweb.pdf, http://www.engineeringtoolbox.com

C_p= Specific heat of air, 0.24 Btu/lbm-°F

ΔT = Dry-bulb temperature difference between A1/A4 and A6, °F

ΔW = Humidity ratio difference between A1/A4 and A6, lbm

$\dot{m}_{scale}$= Average flowrate of condensate mass collected from ID section, lbs

$h_{vap,water}$= Latent heat of vaporization of water, 970.4 Btu/lb

Using the equations described, the following cooling capacity calculation methods were established:

1. Refrigerant enthalpy method
   - Using refrigerant mass flow measurement and the enthalpy difference across the ID coil, calculated at refrigerant-side state points R1 & R8 (where enthalpy at R8= enthalpy at R6)
2. Refrigerant enthalpy method, non-useful superheat removed
   - Using refrigerant mass flow measurement and the enthalpy difference across the ID coil, calculated at refrigerant-side state points R1a & R8 (where enthalpy at R8= enthalpy at R6)
3. Refrigerant enthalpies: heat rejection – heat of compression
   - Using refrigerant mass flow measurement and the difference between the enthalpy changes across the OD coil (heat rejection) and the compressor (heat of compression), at refrigerant-side state points R4, R5, R2, & R3
4. Refrigerant enthalpy heat rejection – electric-side compressor power
   - Using refrigerant mass flow measurement and the enthalpy change across the OD coil (heat rejection) at refrigerant-side state points R4 & R5, and the power measured at the compressor (converted to Btu/h)
5. Air-enthalpy method, enthalpy at return air and supply air, add ID fan heat
   - Using the measured airflow rate, and enthalpy difference across the ID coil at the air-side state points A1 & A6, add the indoor fan power (converted to Btu/h)
6. Air-enthalpy method, “mixed” air inlet and supply air + ID fan heat
   - Using the measured airflow rate, and enthalpy difference across the ID coil at the air-side state points A4 & A6, add the indoor fan power (converted to Btu/h)
7. Air-side sensible + psychrometric latent (RA & SA)
   - Using the measured airflow rate, and the sum of the latent and sensible changes at the air-side state points A1 & A6
8. Air-side sensible + condensate scale latent (RA & SA)
   - Using the measured airflow rate, the latent capacity calculated from mass of condensate collected, and sensible changes at the air-side state points A1 & A6
9. Air-side sensible + psychrometric latent (MA & SA)
   - Using the measured airflow rate, and the sum of the latent and sensible changes at the air-side state points A4 & A6
10. Air-side sensible + condensate scale latent (MA & SA)

- Using the measured airflow rate, the latent capacity calculated from mass of condensate collected, and sensible changes at the air-side state points A4 & A6

Heating capacity calculations are generally similar, with adjustments for the change/directionality of the refrigeration cycle, interaction with fan heat, and zero latent effects.

$$\dot{Q}_{gross-heat\,(ref)} = \dot{m} \times \Delta h_{ID\,coil\,(ref)}$$

$$\dot{Q}_{gross-heat\,(ref)} = \dot{m} \times \left(\Delta h_{OD\,coil\,(ref)} + \Delta h_{comp\,(ref)}\right)$$

$$\dot{Q}_{gross-heat\,(ref)} = \dot{m} \times \Delta h_{OD\,coil\,(ref)} + C1 \times P_{comp}$$

$$\dot{Q}_{gross-heat\,(air)} = \dot{\forall} \times \rho \times \Delta h_{ID\,coil\,(air)} - C1 \times P_{ID\,Fan}$$

$$\dot{Q}_{gross-heat\,(air)} = \dot{Q}_{sensible} - C1 \times P_{ID\,Fan}$$

$$\dot{Q}_{sensible} = \dot{\forall} \times \rho \times C_p \times \Delta T$$

Where

$\dot{Q}_{gross-heat\,(ref)}$ = Gross heating capacity, refrigerant-side calculation, Btu/h

$\dot{m}$ = Refrigerant mass flow rate, lb/h

$\Delta h_{ID\,coil\,(ref)}$= Refrigerant-side enthalpy change between R1/R1a and R8, Btu/lb

$\Delta h_{OD\,coil\,(ref)}$= Refrigerant-side enthalpy change between R4 and R5, Btu/lb

$\Delta h_{comp\,(ref)}$= Refrigerant-side enthalpy change between R2 and R3, Btu/lb

$C1$ = Conversion factor, 3.413, Btu/h per Watt

P_{comp}= Electrical power measured at the compressor, Watts

$\dot{Q}_{gross-heat\,(air)}$ = Gross heating capacity, air-side calculation, Btu/h

$\dot{\forall}$ = ID air volumetric flowrate, SCFM

ρ = Density of standard air, 0.0765 lbm/ft^3

$\Delta h_{ID\,coil\,(air)}$= Air-side enthalpy change between A1/A4 and A6, Btu/lb

$P_{ID\,Fan}$ = Electrical power measured at ID fan, Watts

$\dot{Q}_{sensible}$= Sensible cooling capacity, air-side calculation, Btu/h

C_p= Specific heat of air, 0.24 Btu/lbm-°F

ΔT = Dry-bulb temperature difference between A1/A4 and A6, °F

Using the equations described, the following heating capacity calculation methods were established:

1. Refrigerant enthalpy method
    - Using refrigerant mass flow measurement and the enthalpy difference across the ID coil, calculated at refrigerant-side state points R1 & R8 (where enthalpy at R8= enthalpy at R6)
2. Refrigerant enthalpy method, non-useful superheat removed
    - Using refrigerant mass flow measurement and the enthalpy difference across the ID coil, calculated at refrigerant-side state points R1a & R8 (where enthalpy at R8= enthalpy at R6)
3. Refrigerant enthalpies: heat absorbed + heat of compression
    - Using refrigerant mass flow measurement and the difference between the enthalpy changes across the OD coil (heat absorbed) and the compressor (heat of compression), at refrigerant-side state points R4, R5, R2, & R3
4. Refrigerant enthalpy heat absorbed + electric-side compressor power
    - Using refrigerant mass flow measurement and the enthalpy change across the OD coil (heat rejection) at refrigerant-side state points R4 & R5, and the power measured at the compressor (converted to Btu/h)
5. Air-enthalpy method, return air and supply air - ID fan heat
    - Using the measured airflow rate, and enthalpy difference across the ID coil at the air-side state points A1 & A6, subtract the indoor fan power (converted to Btu/h)
6. Air-enthalpy method, “mixed” air inlet and supply air - ID fan heat
    - Using the measured airflow rate, and enthalpy difference across the ID coil at the air-side state points A4 & A6, subtract the indoor fan power (converted to Btu/h)
7. Air sensible, return air and supply air - ID fan heat
    - Using the measured airflow rate, and sensible heat gain across the ID coil at the air-side state points A1 & A6, subtract the indoor fan power (converted to Btu/h)
8. Air sensible, “mixed” air inlet and supply air - ID fan heat
    - Using the measured airflow rate, and sensible heat gain across the ID coil at the air-side state points A4 & A6, subtract the indoor fan power (converted to Btu/h)

Table 27 summarizes the laboratory instrumentation used for this project.

Table 27 – Lab Instrumentation

Measurement Category	Description	Make	Model
Refg pressures	Pressure transducer	Setra	C207
Refg/air temperatures	Thermocouples	Masy Systems	Type T, Ultra Premium, FEP 22 awg
		Wilcon Industries	Type T, 24-T-T/T, premium grade
	RTDs	Wilcon Industries	RTD, 3-wire, 4-wire
Air humidity	Dewpoint hygrometer	EdgeTech	DewMaster, DewPrime II
	RH sensor	Vaisala	PTU303
Air condensate mass, refrigerant charging mass	Balance	A&D	HP30k
Electrical	Power analyzer	Hioki	3169
	Clamp ammeters	Hioki	9660
	Clamp ammeters	Hioki	9694
Refg mass flow	Coriolis mass flow meter	Endress Hauser	Promass 80F
Air flow	ASHRAE flow meas box - pressure	Ashcroft	IXLdp
	ASHRAE flow meas box - humidity	Vaisala	HMP233
Air pressures	Static pressure taps	Mamac	PR-274

Figure 11 through Figure 14 show examples of equipment/instrumentation used for this project.

Figure 11. Booster fan ID Section, ASHRAE Flow Measurement Box

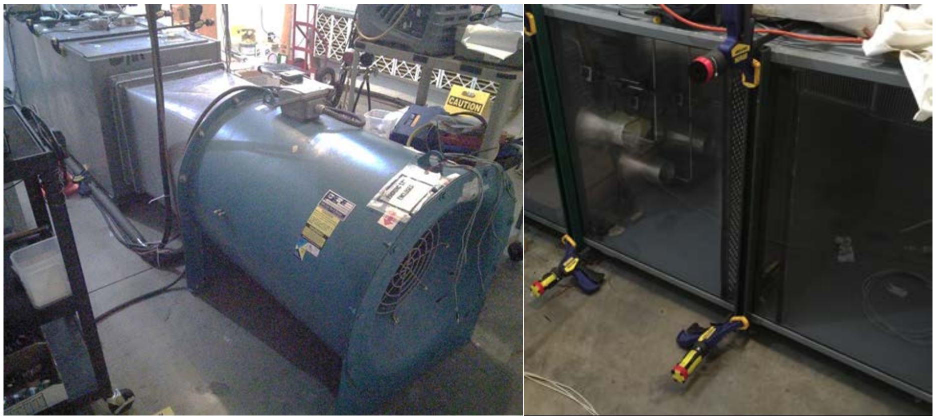


Figure 12. Ducted Test RTU, OD Chamber Room Conditioning Apparatus, & ID Section Condensate Measurement

Figure 13. Refrigerant Mass Flow Meter & Compressor Instrumentation

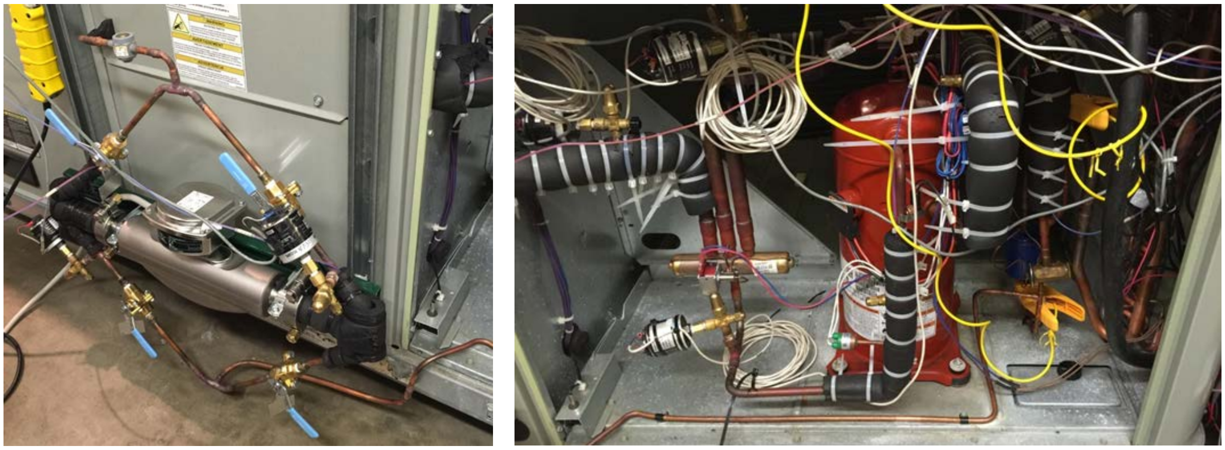


Figure 14. Sealed relief air (left) and outside air inlet (right)

Many noteworthy challenges were encountered during the equipment procurement and setup process, and summarized as follows:

- The factory economizer equipment was found to be appropriate for vertical ducting configuration. Separate equipment from a 3rd-party design was needed for horizontal ducted setup.
    - Incorrect relief air damper was specified by 3rd party (non-Title 24, see Figure 16)
    - Damage occurred on the low-leakage gaskets for the outside air damper during shipment. Damage was determined to be cosmetic and did not impact the ability to seal effectively (see Figure 17).
    - The economizer module was received pre-wired incorrectly. Upon activation, the economizer FDD displayed an alarm.

    - The economizer damper actuators were configured to operate in reverse: when call for 100% outside air was initiated, the outside air damper was closed in the 0% position
- The RTU was tagged as having been fully charged, but received with no refrigerant
    - The condenser was found to have two major leaks; repairs to condenser were deemed too extensive and would impact performance. A replacement condenser was procured and installed (see Figure 16).
- Inconsistencies in check valve/filter-drier placement, and OD section TXV sensing bulb placement were identified in two versions of the refrigerant circuit diagram
- Large restriction was present in the original check valve, cause was unknown (see Figure 15)
- Transition ducting designed/fabricated by 3rd party required several iterations
    - Initial parts received were "mirror image" and incorrect
    - Design was based on original equipment in vertical ducting configuration, not horizontal
- Ongoing issues were observed in syncing FDD field measurement sensors to the analyzer
    - The data logging mode of the analyzer was unable to handle all of the field measurement sensors simultaneously
    - The analyzer's FDD mode was specified to be able to handle all field measurement sensors simultaneously, but signal loss was a frequent occurrence throughout testing
- The analyzer contained a port which appeared to be for connection to an AC adapter for power, but it was discovered later on from the manufacturer that this function was never enabled; the analyzer and all field sensors were meant to run off of battery power alone, so separate wiring needed to be rigged up for constant power to the battery terminals, to allow for ongoing testing without the need for handling the logistics of replacing batteries

Figure 15. Liquid Line Check Valve (New & Old)

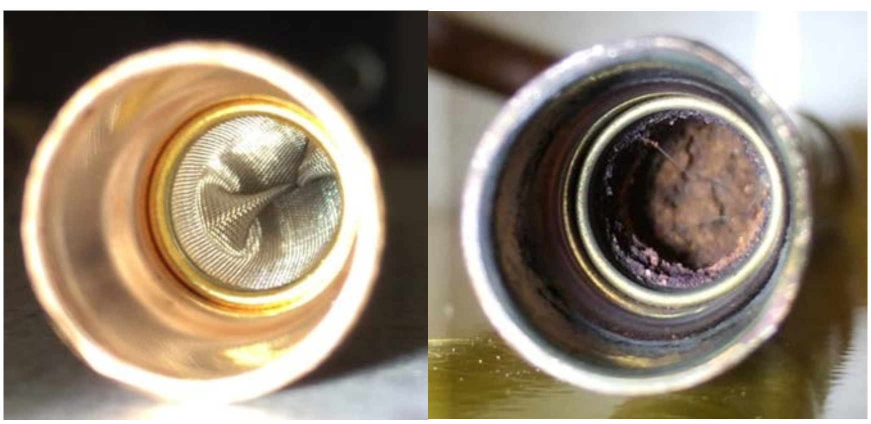


Figure 16. Relief Air Damper (Non-Title 24 Part) & Tracing Condenser Leaks

Figure 17. Outside Air Damper Gasket Damage

Test Scenarios & Procedures

For the steady-state heating and cooling performance tests, the following fault families were established:

- **Indoor (ID) Airflow Restriction Fault**
  ID airflow restrictions may comprise a number of different faults ranging from dirty/clogged filters, duct/register obstructions, ID coil obstructions/damaged fins/ fouling, etc. This fault is imposed as airflow restrictions on the ID coil air-side inlet/outlet.
- **Outdoor (OD) Airflow Restriction Fault**
  OD airflow restrictions may comprise a number of different faults ranging from inlet/outlet obstructions, coil obstructions/damaged fins/fouling, etc. This fault is imposed as an airflow restriction on the OD coil air-side outlet.
- **Low Charge**
  Low charge may be a result of system leaks or from improper servicing practices. It represents a situation where the RTU contains an amount of refrigerant that is significantly below the nominal established by the manufacturer. This fault is imposed through removal of refrigerant.
- **High Charge**
  High charge may be a result of improper servicing practices. It represents a situation where the RTU contains an amount of refrigerant that is significantly above the nominal established by the manufacturer. This fault is imposed through addition of refrigerant.
- **Multiple Fault: Low Charge, ID & OD Airflow Restriction**
  This scenario represents a 3-fault simultaneous occurrence of the low charge, ID and OD airflow restriction faults.

For FDD units 1 through 3, the following baseline characteristics were given as inputs: R410a refrigerant, 5 ton, heat pump, SEER=13. EER=12, TXV, standard efficiency evaporator, 12°F target superheat, OD rated amps = 44.6, power factor 0.95 (default), 1 stage cooling, direct drive ID fan (1-speed) , 10°F target subcooling*.

*10°F target sub cooling was chosen as it is the average sub cooling calculated from characteristics of the RTU charging protocol.

The following describes the procedures for imposing each of the fault families in heating and cooling mode operation.

<u>Cooling mode: Indoor (ID) Airflow Restriction</u>

The cooling mode ID airflow restriction faults were imposed via flat plate restrictions at the inlet to the return air section and the outlet of the supply air section (see Figure 18). The fault intensity is tracked by compressor suction pressure (state point R2) and ID airflow. Baseline airflow was set to 2,000 SCFM. The high intensity fault is considered to be at the point before coil frosting, where the saturated suction temperature is 35F, which corresponds to a suction pressure of roughly 107 psig. 107 psig was achievable at ambient OD conditions of 95F (631 SCFM) and 80F (837 SCFM). The 107 psig suction pressure target was not achievable at the ambient OD condition of 115F: The highest severity restriction achievable resulted in a suction pressure of 114 psig, which equates to a saturated suction temperature of roughly 38F, and required in airflow to 494 SCFM (a 75% reduction!). The low intensity fault was chosen as an ID airflow rate of 1,500 SCFM.

Heating mode: Indoor Airflow Restriction

The heating mode ID airflow restriction faults were imposed via flat plate restrictions at the inlet to the return air section and the outlet of the supply air section (see Figure 18). The fault intensity is tracked by compressor discharge pressure (state point R3) and ID airflow. Baseline airflow was set to 2,000 SCFM. The high intensity fault is considered to be at the point before the RTU shuts off on high pressure switch (cutoff is at 620 psi). 600 psig (517 SCFM) was chosen as the high intensity fault. 520 psig (668 SCFM) and 430 psig (1,049 SCFM) were chosen as the medium and low intensity faults, respectively.

Figure 18. ID Airflow Restriction, Return and Supply Sections

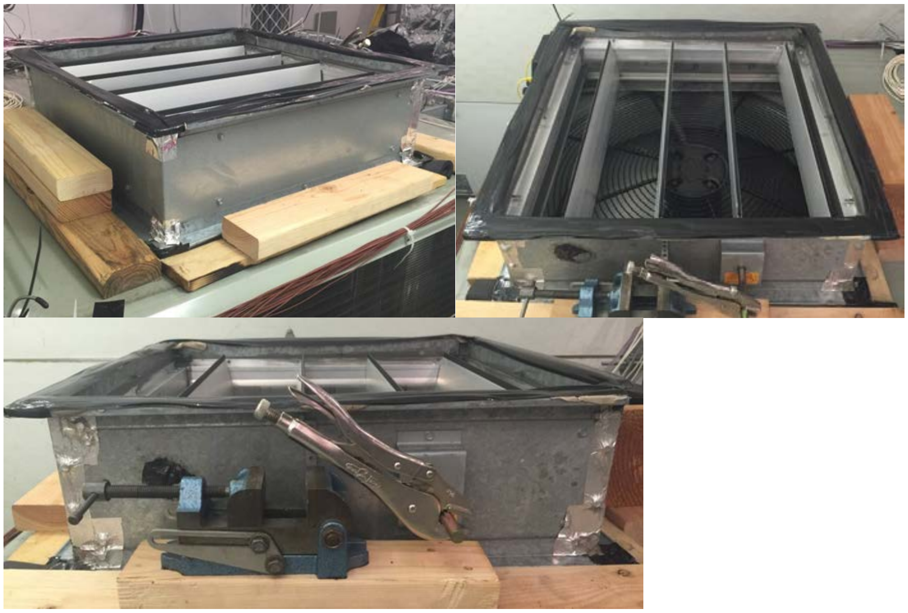
Cooling Mode: Outdoor (OD) Airflow Restriction

The cooling mode OD airflow restriction faults were imposed with a damper on the OD section's outlet (see Figure 19). The fault intensity is tracked by compressor discharge pressure (state point R3) and ID airflow. The high intensity fault is considered to be at the point before the RTU shuts off on high pressure switch (cutoff is at 620 psi). 600 psig (517 SCFM) was chosen as the high intensity fault. 520 psig, 450 psig, and 411 psig were chosen as the low intensity faults for tests 12, 13, and 14, respectively.

Heating Mode: Outdoor (OD) Airflow Restriction

The heating mode OD airflow restriction faults were imposed with a damper on the OD section's outlet (see Figure 19). The fault intensity is tracked by compressor suction pressure (state point R2). The high intensity fault was chosen at 67 psig: this corresponded to the same damper position as cooling mode OD restriction test 16. 77 psig and 87 psig were chosen as the medium and low intensity faults, respectively.

Figure 19. OD Airflow Restriction - Damper



Preliminary testing was considered with a flat plate OD coil outlet obstruction, but ultimately was not used. Flat plate OD coil outlet restriction proved problematic in a few ways:

- It seemed to cause discharge air recirculation back to the condenser inlets.
- The discharge grille protrusion limited the airflow restrictions that could be achieved. This method's highest achievable head pressure was roughly 440 psig at 95F outdoor ambient conditions (baseline discharge pressure is around 380 psig at 95F OD ambient). This method was unable to force the RTU to shut off on high pressure switch.
- Position of flat plate more difficult to control than damper position restriction.

Figure 20. OD Airflow Restriction – Flat Plate

<u>Cooling mode and heating mode: low and high charge</u>

Cooling and heating mode high and low charge faults were imposed through a weigh in/out procedure that leveraged a precise digital balance (see Figure 21). Fault intensity is tracked in pounds of refrigerant. 10% increments of 1.1 pounds were established (normalized to 11 pounds nominal charge, which includes additional refrigerant for added piping/instrumentation). Anytime refrigerant was added to the system, new refrigerant was used. Reclaimed refrigerant was never re-used.

Figure 21. Charge faults: digital balance and refrigerant

Cooling mode and heating mode: multiple faults

Multiple faults were imposed in the order of: low charge, OD airflow restriction, and ID airflow restriction, using the procedures previously described. In establishing increments of repeatable, multiple fault tests, it is important to consider the order each fault is imposed; in lieu of available OD airflow measurements, OD airflow faults are tracked with compressor discharge pressures, which are impacted by low charge and ID airflow.

For the economizer FDD testing, the following faults were established:

- **Economizer stuck open**
  This fault was imposed through a physical obstruction of the outside air inlet damper, which was in the 100% open position.
- **Economizer stuck at minimum position**
  This fault was imposed through a physical obstruction of the outside air inlet damper, which was in the 0% closed position.
- **Bad/unplugged actuator**
  This fault was imposed through electrical disconnection of the outside air inlet actuator.
- **Sensor failure**
  This fault was imposed through electrical disconnection of two temperature sensors: outside air and supply air.
- **Actuator mechanically disconnected**
  This fault was imposed through mechanical disconnection between the outside air inlet actuator and damper.

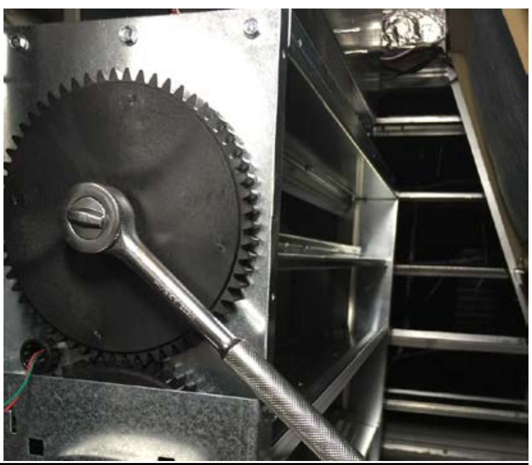
Generally, these tests are completed by interfacing with the thermostat, the economizer, and FDD unit 4. The RTU is disabled into the OFF mode. The thermostat is set to call for cooling/ID fan operation, and establishes an "occupied" mode. The economizer is configured in fixed DB control. The minimum position is set to 0%, and the high limit is set to 80°F. Ambient temperature is roughly 76°F, which causes the economizer to open to the 100% fully open position.

The following describes the procedures for imposing each of the economizer faults, where the tester always started from the condition previously described.

Economizer stuck open

A ratchet tool was rigged to prevent physical movement of the outside air inlet damper blade (see Figure 22); the clockwise closing movement of the damper was prevented. The high limit was adjusted to 60°F, which resulted in a call for the outside air damper to close. As the damper attempted to close to the 0% position, it became stuck and eventually registered a fault. The high limit was then set back to 80°F, which caused the damper to return to the open position, and the fault condition to clear.

Figure 22. Economizer stuck open



Economizer stuck at minimum position

The high limit was set to 60°F, which caused the outside air damper to close to the 0% position. A ratchet tool was then rigged to prevent physical movement of the outside air inlet damper blade (see Figure 23); the counter-clockwise opening movement of the damper was prevented. The high limit was then set to 80°F, which caused a call for the outside air damper to open. As the damper attempted to open to the 100% position, it became stuck and eventually registered a fault. The high limit was then set back to 60°F, which caused the damper to return to the closed position, and the fault condition to clear.

Figure 23. Charge faults: digital balance and refrigerant

Bad/unplugged actuator

The economizer had four cables associated with electrical connections to the actuators: actuator supply common, actuator supply hot, actuator control output, and actuator feedback signal. Each cable was isolated and disconnected separately. Some registered faults instantly; others required a call for damper movement, and some time to register the fault.

Sensor failure

The economizer had two temperature sensors associated with fixed DB control: the outside air and supply air temperatures. Upon disconnecting these sensors, faults were registered instantly.

Actuator mechanically disconnected

The mechanical linkage between the outside air inlet damper and actuator was disconnected. Then a call for damper movement was initiated.

Test Scenarios

Table 28 and Table 29 show test scenarios, grouped by fault families and operating conditions. Additionally, charge, and ID/OD fault intensities are summarized. In this manner, it is easier to understand the structure of the faults and test conditions being explored, but testing faults in this order is not the ideal sequence. Generally, cooling mode fault tests are conducted at intensities of “low” or “high”, each of which were tested at three OD test chamber conditions, anchored at one ID test chamber condition. In heating mode, tests are anchored to a single ID and OD condition, with fault intensities at “low”, “medium”, and “high”.

Table 28 – Test Scenario List: Prelim, Baseline, & Economizer

#	Mode	Fault	ID Condition		OD Condition		OD/ID Airflow Restriction Fault Tracking			
			DB (F)	WB (F)	DB (F)	WB (F)	Charge (lbs)	Discharge Press (psig)	Suction Press (psig)	ID Airflow (SCFM)
1	Cool	None, Baseline	75	62.5	115	-	11	-	-	2,000
2					95	-				
3					80	-				
4	Heat		70	(60 max)	47	43 (72.7% RH)				
5	Cool	T-24 Economizer Test Procedures	-	-	-	-				-

Table 29 – Test Scenario List: Cooling & Heating Mode Single & Multiple Faults

#	Mode	Fault		ID Condition		OD Condition		OD/ID Airflow Restriction Fault Tracking			
				DB (F)	WB (F)	DB (F)	WB (F)	Charge (lbs)	Discharge Press (psig)	Suction Press (psig)	ID Airflow (SCFM)
6	Cool	Single	Indoor coil airflow restriction	75	62.5	115	-	11	-	130	1,500
7						95				125	
8						80				121	
9						115				114	494
10						95				107	631
11						80					837
12			Outdoor coil airflow restriction			115			520	-	2,000
13						95			450		
14						80			411		
15						115			604		
16						95			606		
17						80			604		
18			Low Charge			115		9.9	-		
19						95					
20						80					
21						115		7.7			
22						95					
23						80					
24			High Charge			115		12.1			
25						95					
26						80					
27						115		14.3			
28						95					
29						80					
30	Cool	Multiple	Low Charge, ID/OD airflow restriction	75	62.5	115	-	9.9	520*	-	1,503
31						95			450*		1,474
32						80			410*		1,489
33						115		7.7	600*		499
34						95		7.7			633
35						80		7.7			840
36	Heat	Single	Indoor coil airflow restriction	70	60 (max)	47	43 (72.7% RH)	11	430	-	1,049
37									520		668
38									600		517
39			Outdoor coil airflow restriction						-	87**	-
40										77**	
41										67**	
42			Low Charge					9.9	-		2,000
43								8.8			
44								7.7			
45			High Charge					12.1			
46								13.2			
47								14.3			
48		Multiple	Low Charge, ID/OD airflow					9.9	-	89	1,052
49								7.7		69	521

*Discharge pressure was set, then ID airflow restriction was imposed, changing discharge pressure

**Outdoor airflow restrictions in heating mode result in frosted coils, which changes the average suction pressure

Table 30 through Table 32 show the test sequence, designed to minimize the iterations of refrigerant charge adjustment.

Table 30 – Test Sequencing: Round 1

#	Mode	Fault		ID Condition DB (F)	ID Condition WB (F)	OD Condition DB (F)	OD Condition WB (F)	OD/ID Airflow Restriction Fault Tracking: Charge (lbs)	Discharge Press (psig)	Suction Press (psig)	ID Airflow (SCFM)
i	Cool	None, Verify AHRI ID/OD		80	67	95	-	11			2,000
ii	Heat			70	60	47	43				
1	Cool	None, Baseline		75	62.5	115	-				
2						95	-				
3						80	-				
4	Heat			70	(60 max)	47	43 (72.7% RH)				
6	Cool	Single	Indoor coil airflow restriction	75	62.5	115	-		-	130	1,500
7						95				125	
8						80				121	
9						115				114	494
10						95				107	631
11						80					837
12			Outdoor coil airflow restriction	75	62.5	115	-		520	-	2,000
13						95			450		
14						80			411		
15						115			604		
16						95			606		
17						80			604		
36	Heat		Indoor coil airflow restriction	70	60 (max)	47	43 (72.7% RH)		430	-	1,049
37									520		668
38									600		517
39			Outdoor coil airflow restriction						-	87**	-
40										77**	
41										67**	

Table 31 – Test Sequencing: Round 2

#	Mode	Fault		ID Condition DB (F)	ID Condition WB (F)	OD Condition DB (F)	OD Condition WB (F)	OD/ID Airflow Restriction Fault Tracking: Charge (lbs)	Discharge Press (psig)	Suction Press (psig)	ID Airflow (SCFM)
27	Cool	Single	High Charge	75	62.5	115	-	14.3	-		2,000
28						95					
29						80					
47	Heat			70	60 max	47	43				
46								13.2			
45								12.1			
26	Cool			75	62.5	80	-				
25						95					
24						115					

Table 32 – Test Sequencing: Round 3

#	Mode	Fault		ID Condition		OD Condition		OD/ID Airflow Restriction Fault Tracking			
				DB (F)	WB (F)	DB (F)	WB (F)	Charge (lbs)	Discharge Press (psig)	Suction Press (psig)	ID Airflow (SCFM)
18	Cool	Single	Low Charge	75	62.5	115	-	9.9	-		2,000
30		Multiple	Low Charge, ID/OD airflow restriction						520*	-	1,503
19		Single	Low Charge			95			-		2,000
31		Multiple	Low Charge, ID/OD airflow restriction						450*	-	1,474
20		Single	Low Charge			80			-		2,000
32		Multiple	Low Charge, ID/OD airflow restriction						410*	-	1,489
42	Heat	Single	Low Charge	70	60 max	47	43		-		2,000
48		Multiple	Low Charge, ID/OD airflow restriction							89	1,052
43		Single	Low Charge					8.8	-		2,000
44								7.7			
49		Multiple	Low Charge, ID/OD airflow restriction							69	521
23	Cool	Single	Low Charge	75	62.5	80	-		-		2,000
35		Multiple	Low Charge, ID/OD airflow restriction						600	-	840
22		Single	Low Charge			95			-		2,000
34		Multiple	Low Charge, ID/OD airflow restriction						600	-	633
21		Single	Low Charge			115			-		2,000
33		Multiple	Low Charge, ID/OD airflow restriction						600	-	499

Results: Exploring the Impacts of Faults

The steady-state heating and cooling performance tests allowed for investigation of performance impacts. The following figures show cooling/heating capacity and power impacts on both a normalized and absolute value basis. Figure 24 illustrates the impacts from OD ambient condition variation on baseline cooling capacity and power. Figure 25 through Figure 33 illustrate the impacts from single faults on cooling capacity and power, at the three ambient OD conditions of 115F, 95F, and 80F. Figure 34 through Figure 36 illustrate the impacts from multiple faults on cooling capacity and power, at the three ambient OD conditions of 115F, 95F, and 80F. Figure 37 through Figure 39 show the heating mode impacts of single faults on heating capacity and power. Figure 40 shows the heating mode impacts of multiple faults on heating capacity and power.

Figure 24. Baseline OD Ambient Fluctuation (Cooling Mode): Power & Cooling Impacts

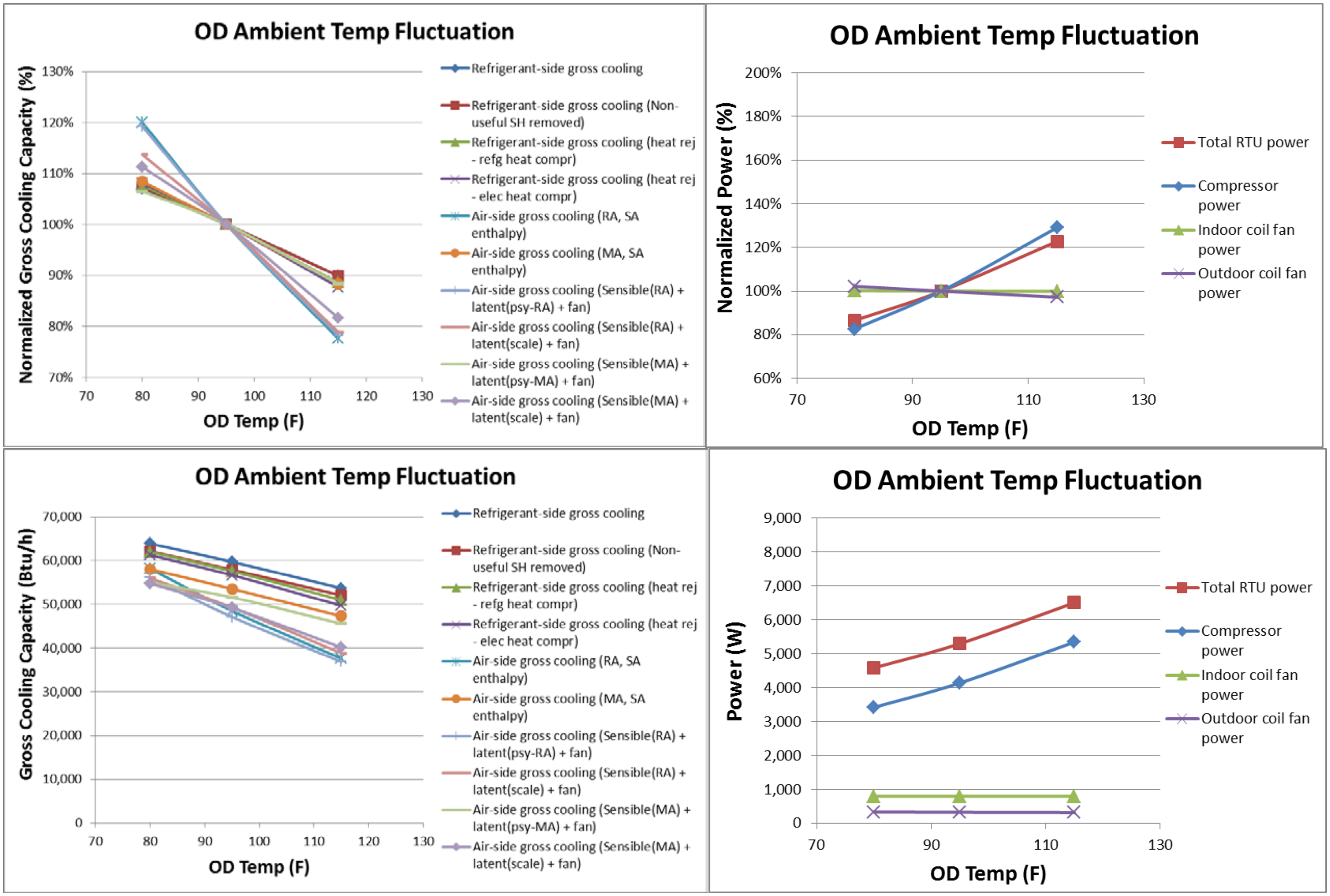


Figure 25. ID Airflow Restriction (115F OD, Cooling Mode): Power & Cooling Impacts

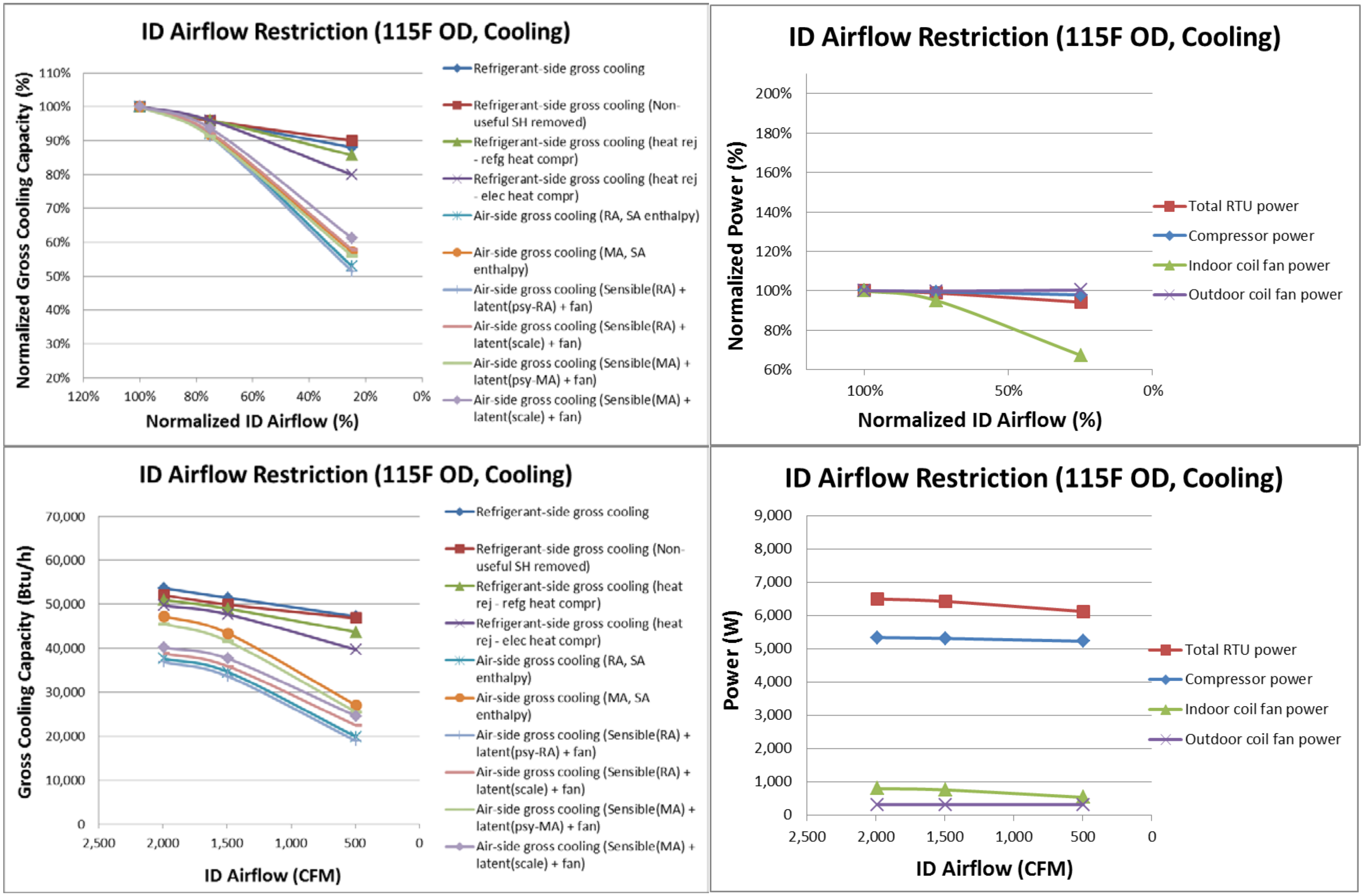


Figure 26. ID Airflow Restriction (95F OD, Cooling Mode): Power & Cooling Impacts

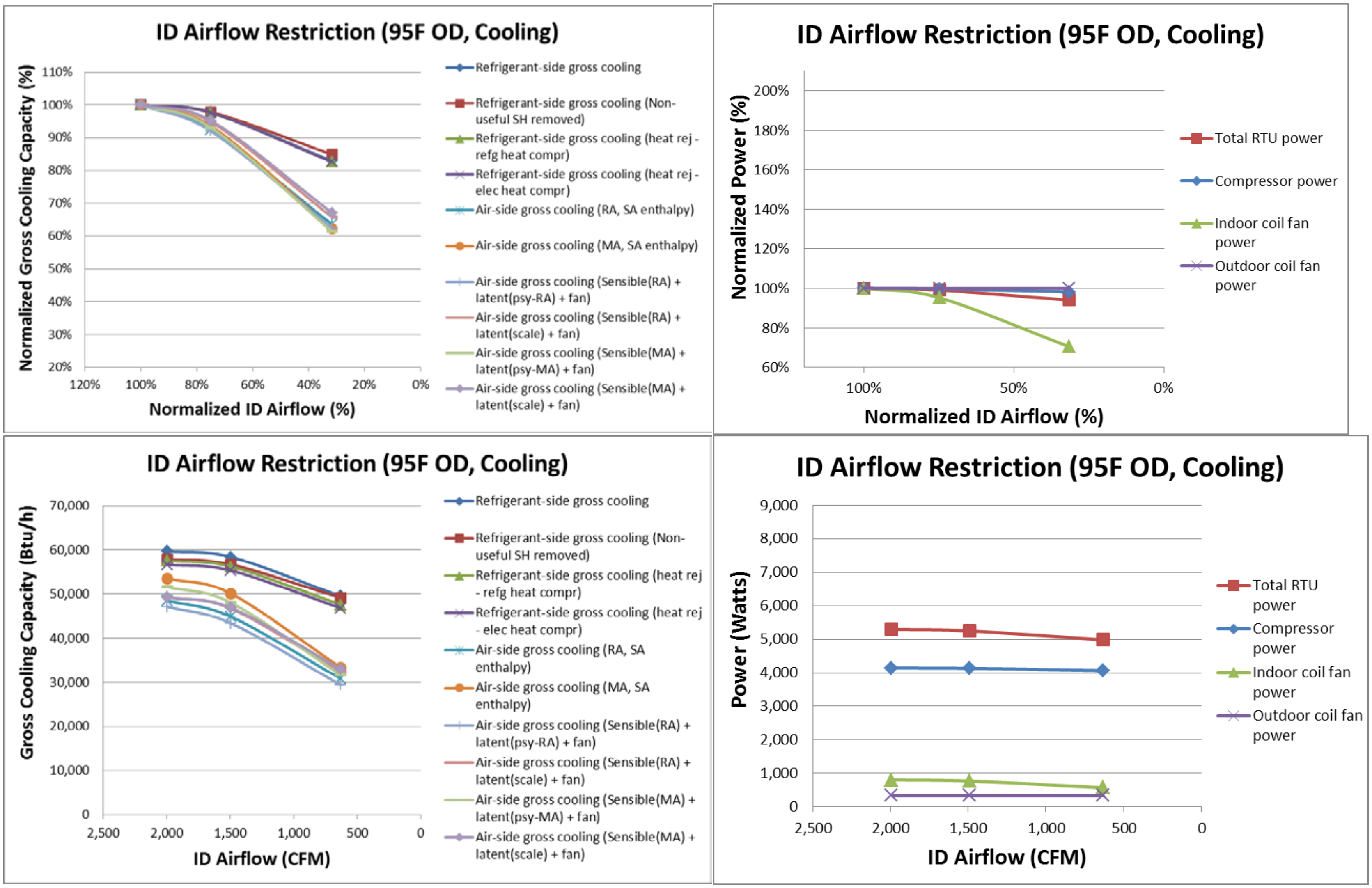


Figure 27. ID Airflow Restriction (80F OD, Cooling Mode): Power & Cooling Impacts

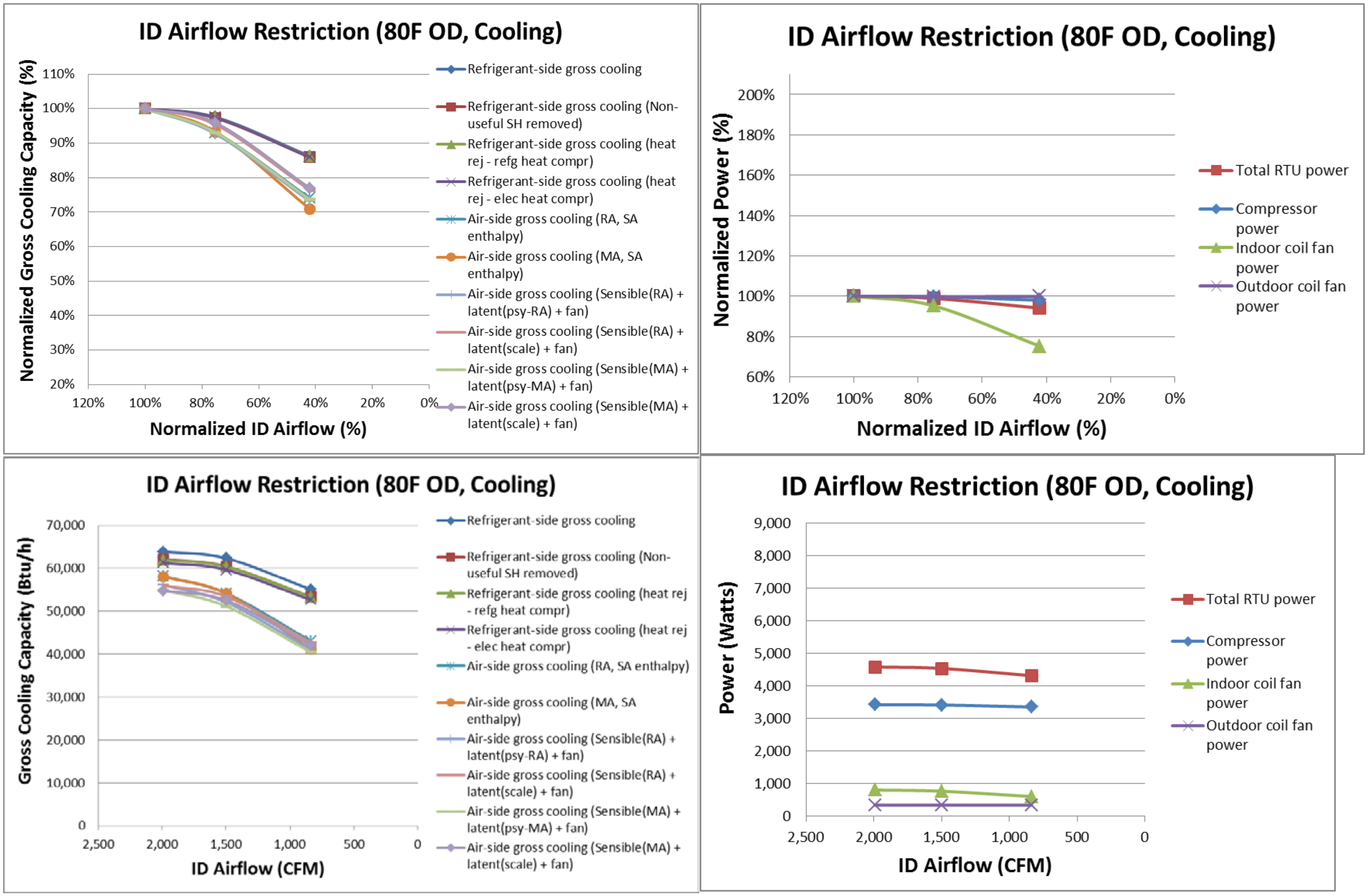


Figure 28. OD Airflow Restriction (115F OD, Cooling Mode): Power & Cooling Impacts

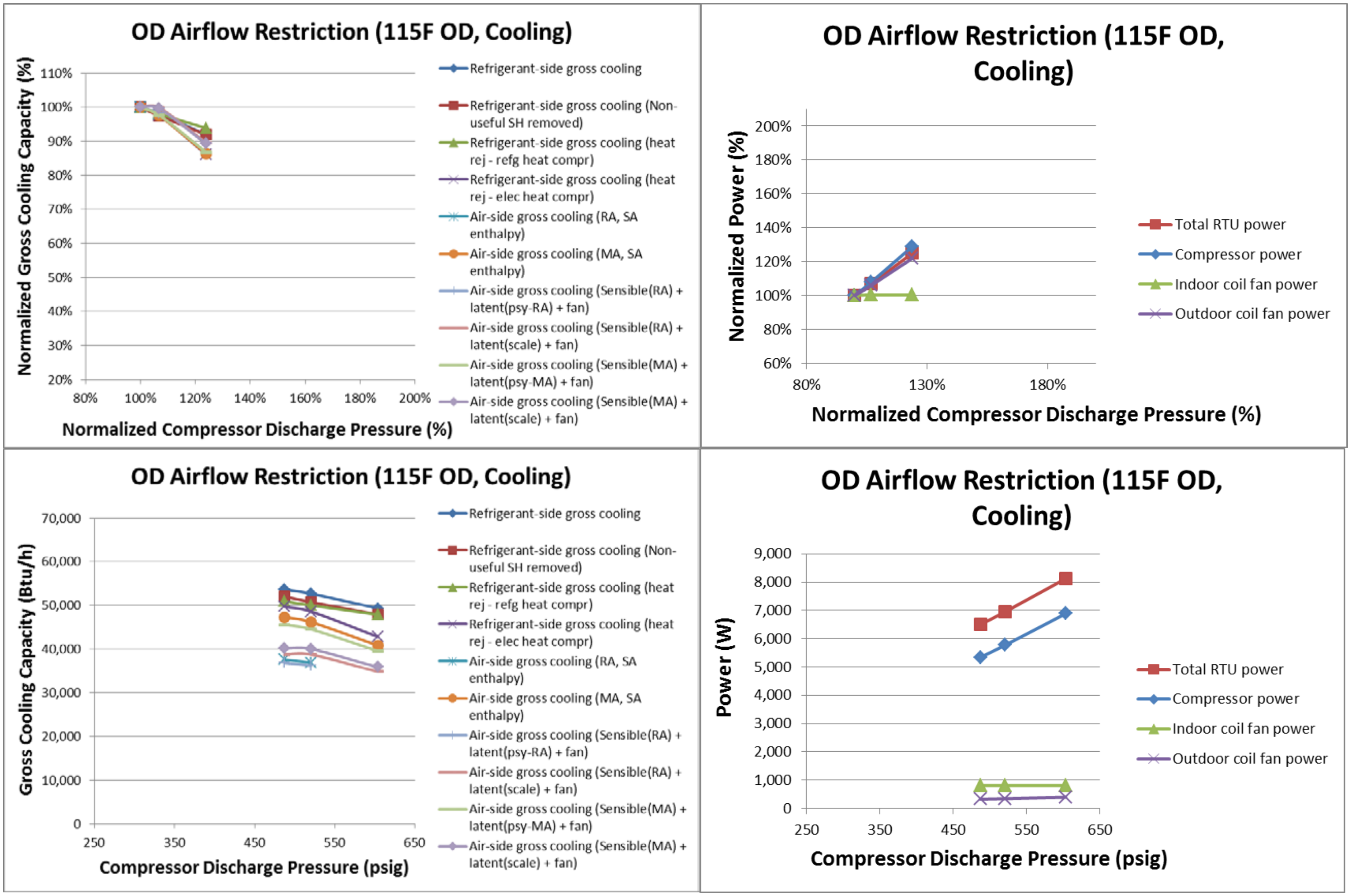


Figure 29. OD Airflow Restriction (95F OD, Cooling Mode): Power & Cooling Impacts

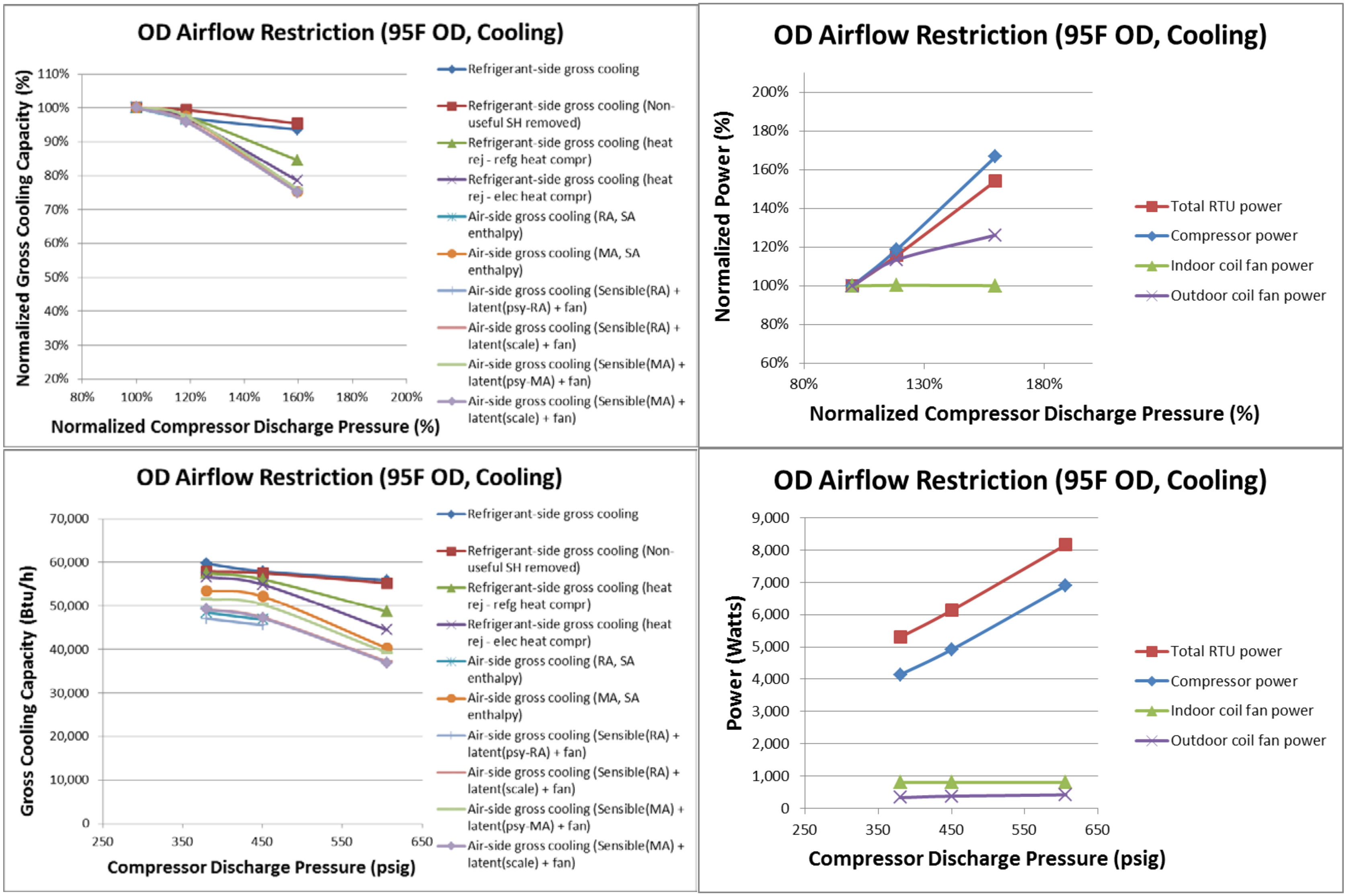


Figure 30. OD Airflow Restriction (80F OD, Cooling Mode): Power & Cooling Impacts

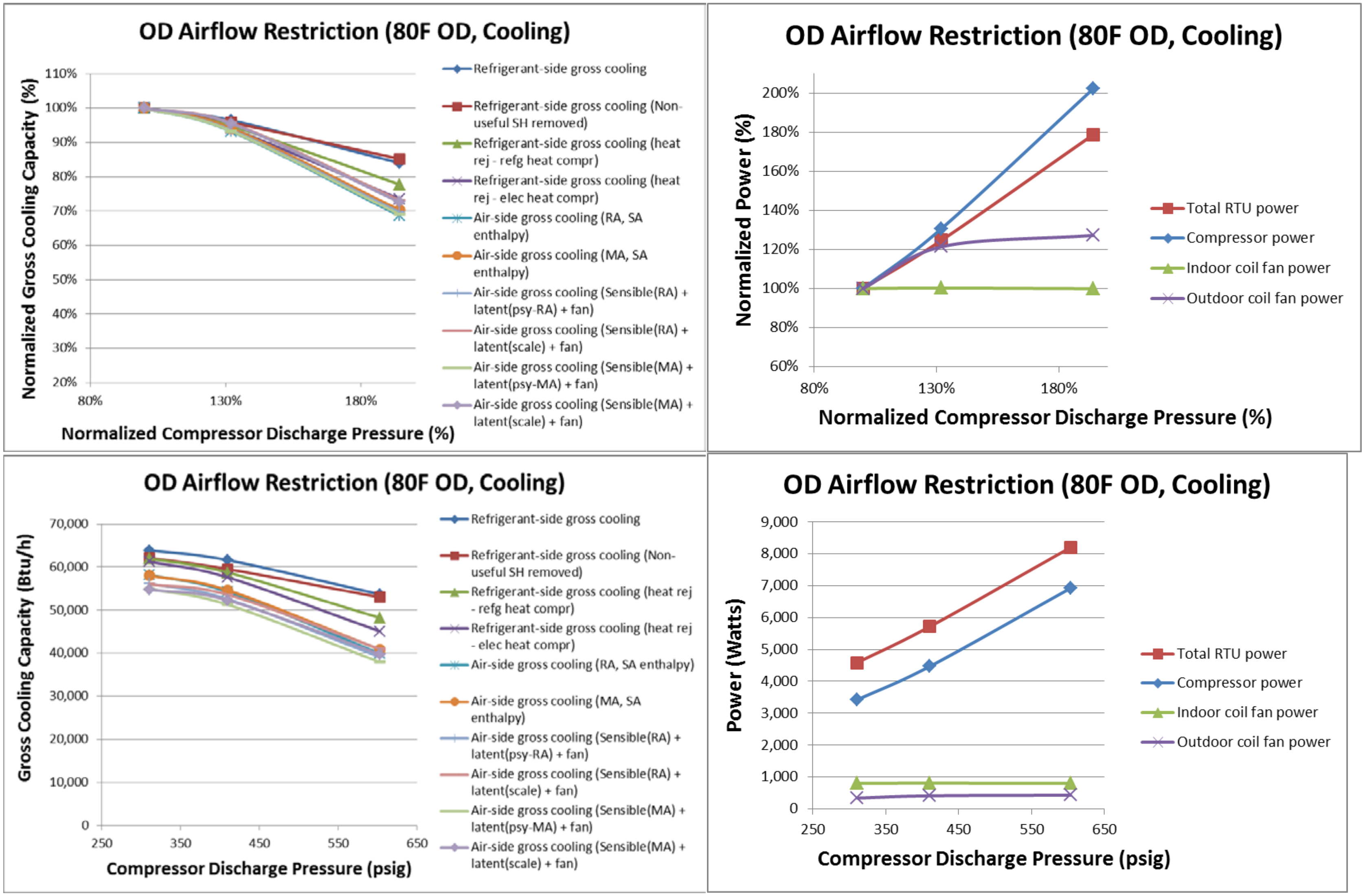


Figure 31. Improper Charge (115F OD, Cooling Mode): Power & Cooling Impacts

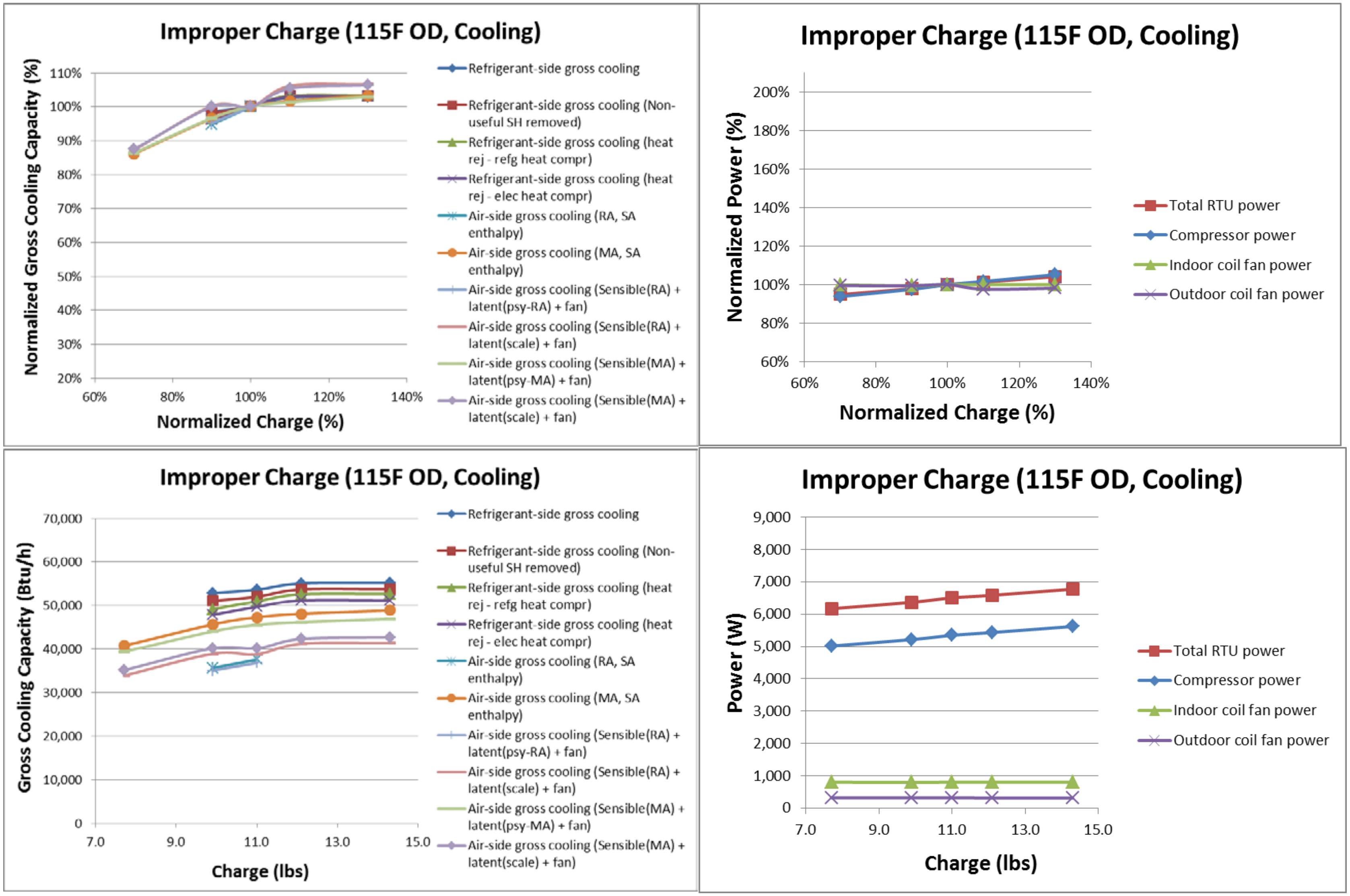


Figure 32. Improper Charge (95F OD, Cooling Mode): Power & Cooling Impacts

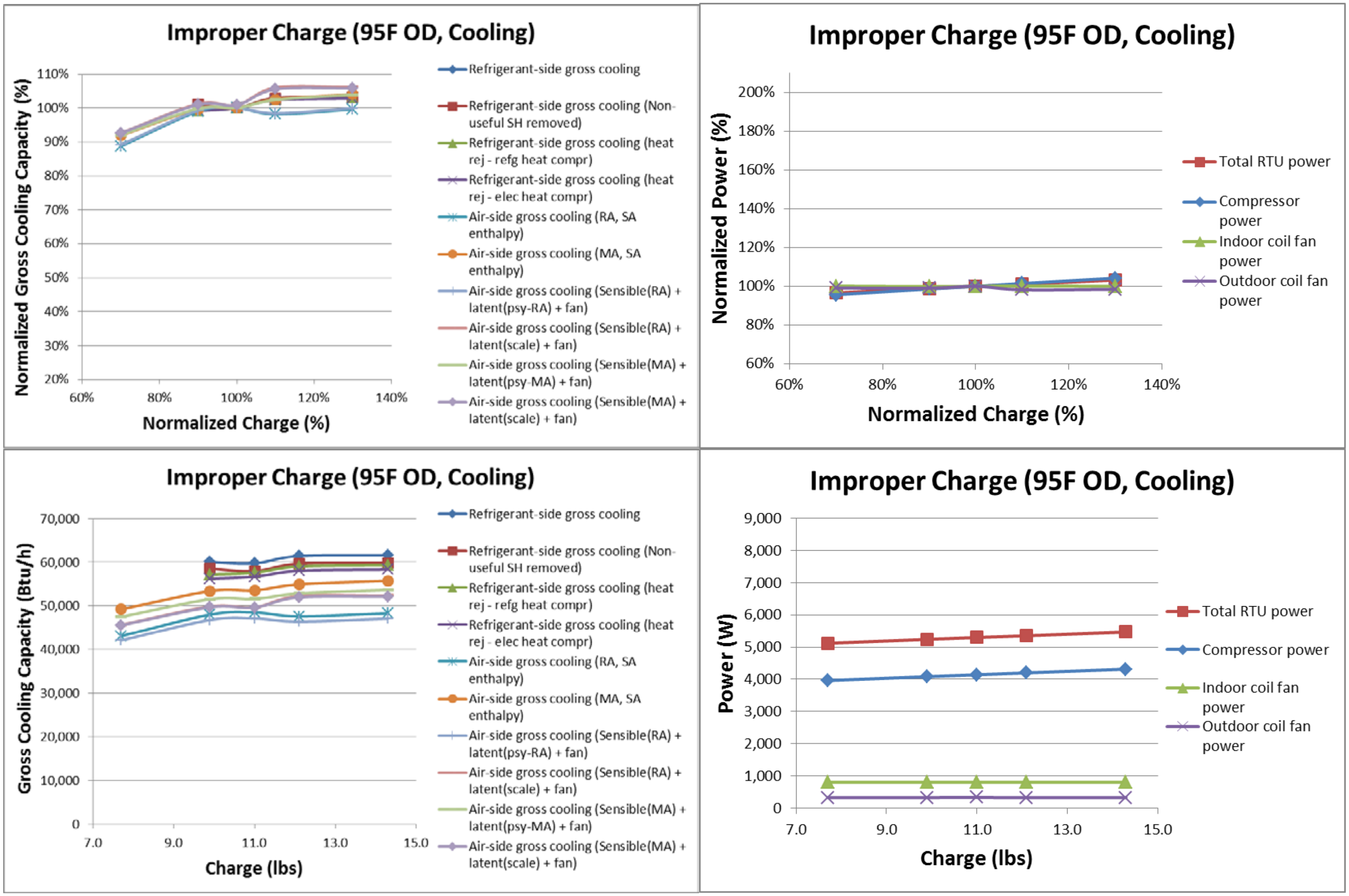


Figure 33. Improper Charge (80F OD, Cooling Mode): Power & Cooling Impacts

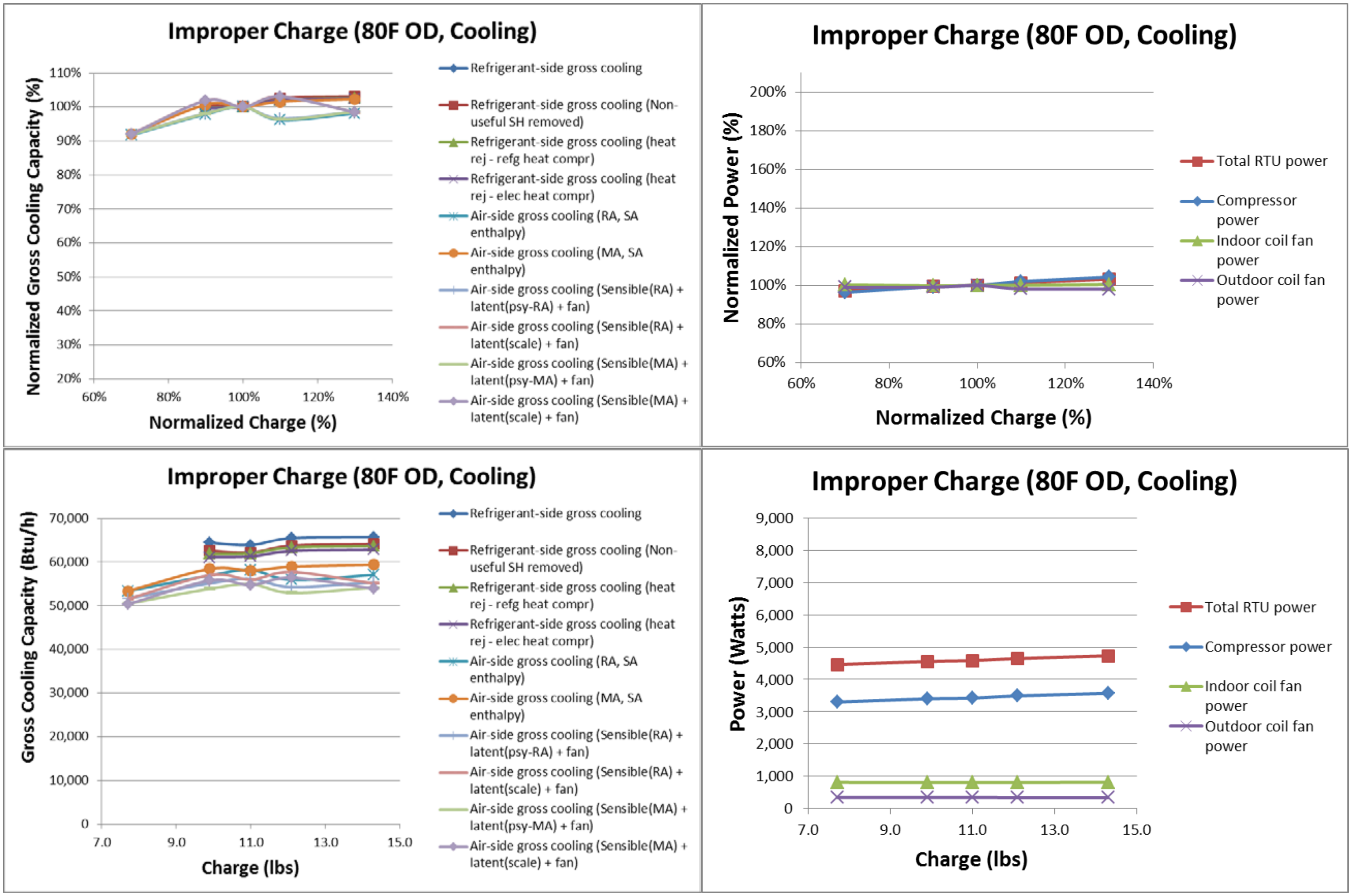


Figure 34. Multiple Faults: Low ID/OD Airflow & Charge (115F OD, Cooling Mode): Power & Cooling Impacts

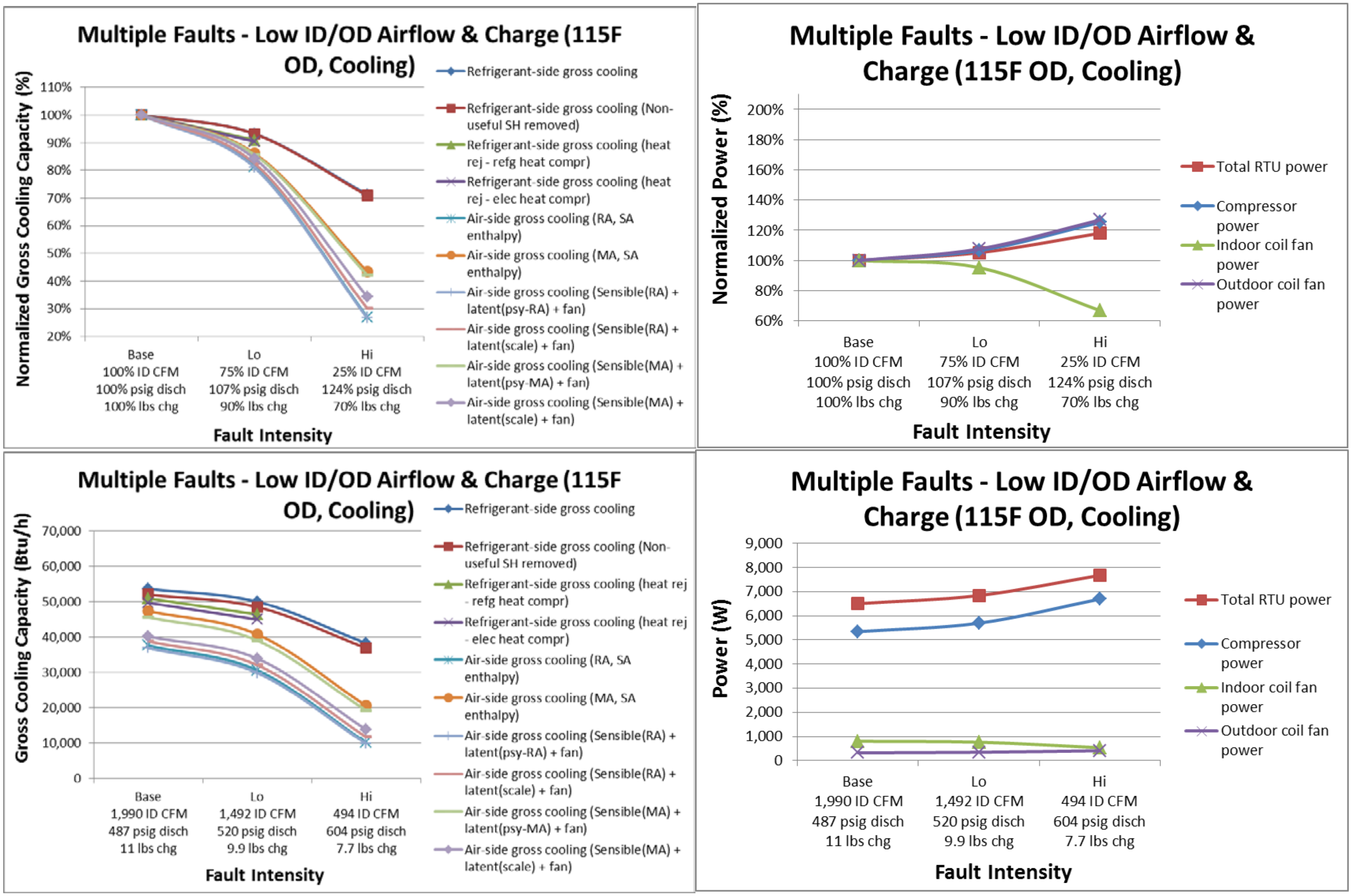


Figure 35. Multiple Faults: Low ID/OD Airflow & Charge (95F OD, Cooling Mode): Power & Cooling Impacts

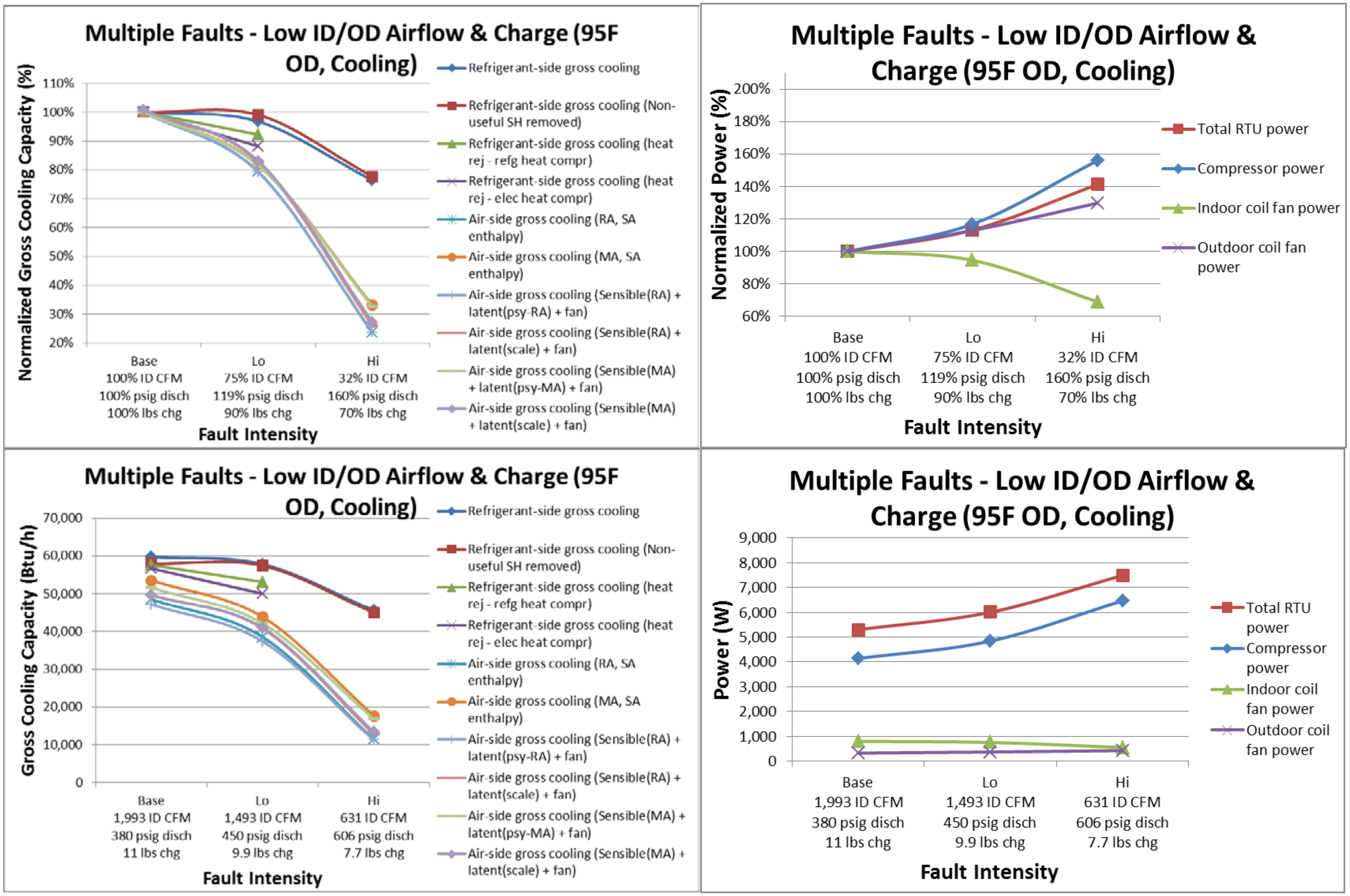


Figure 36. Multiple Faults: Low ID/OD Airflow & Charge (80F OD, Cooling Mode): Power & Cooling Impacts

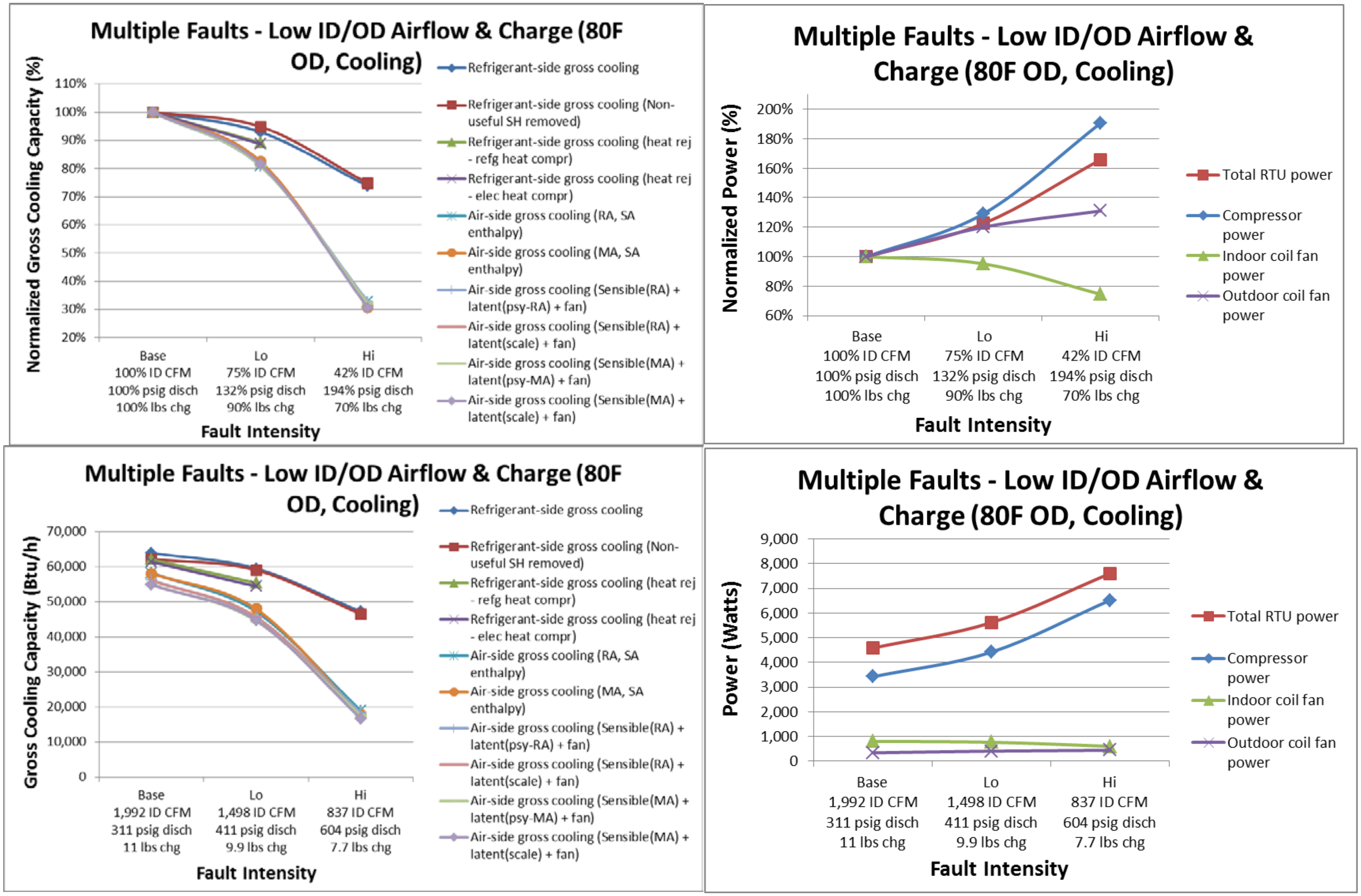


Figure 37. ID Airflow Restriction (Heating Mode): Power & Cooling Impacts

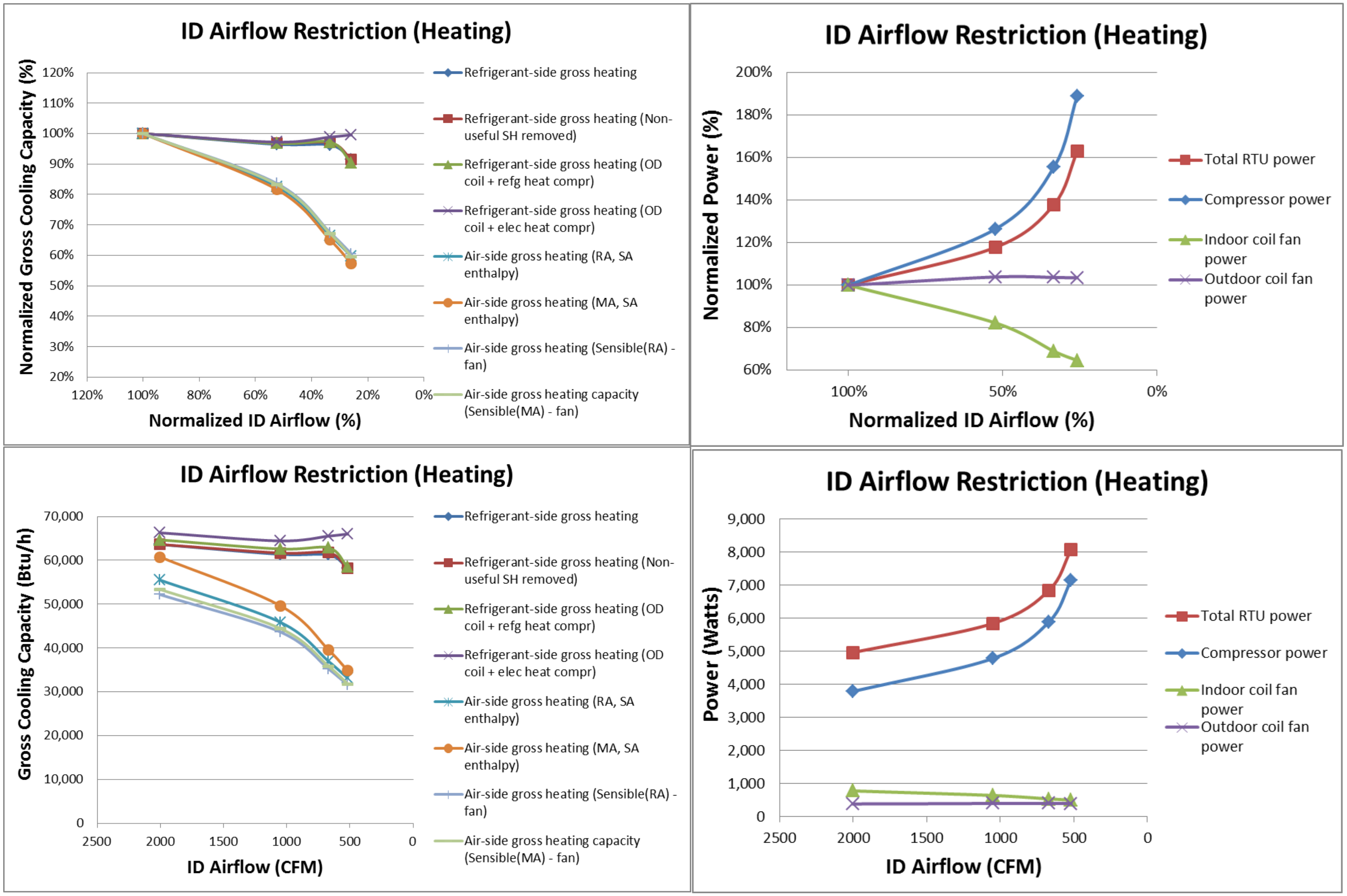


Figure 38. OD Airflow Restriction (Heating Mode): Power & Cooling Impacts

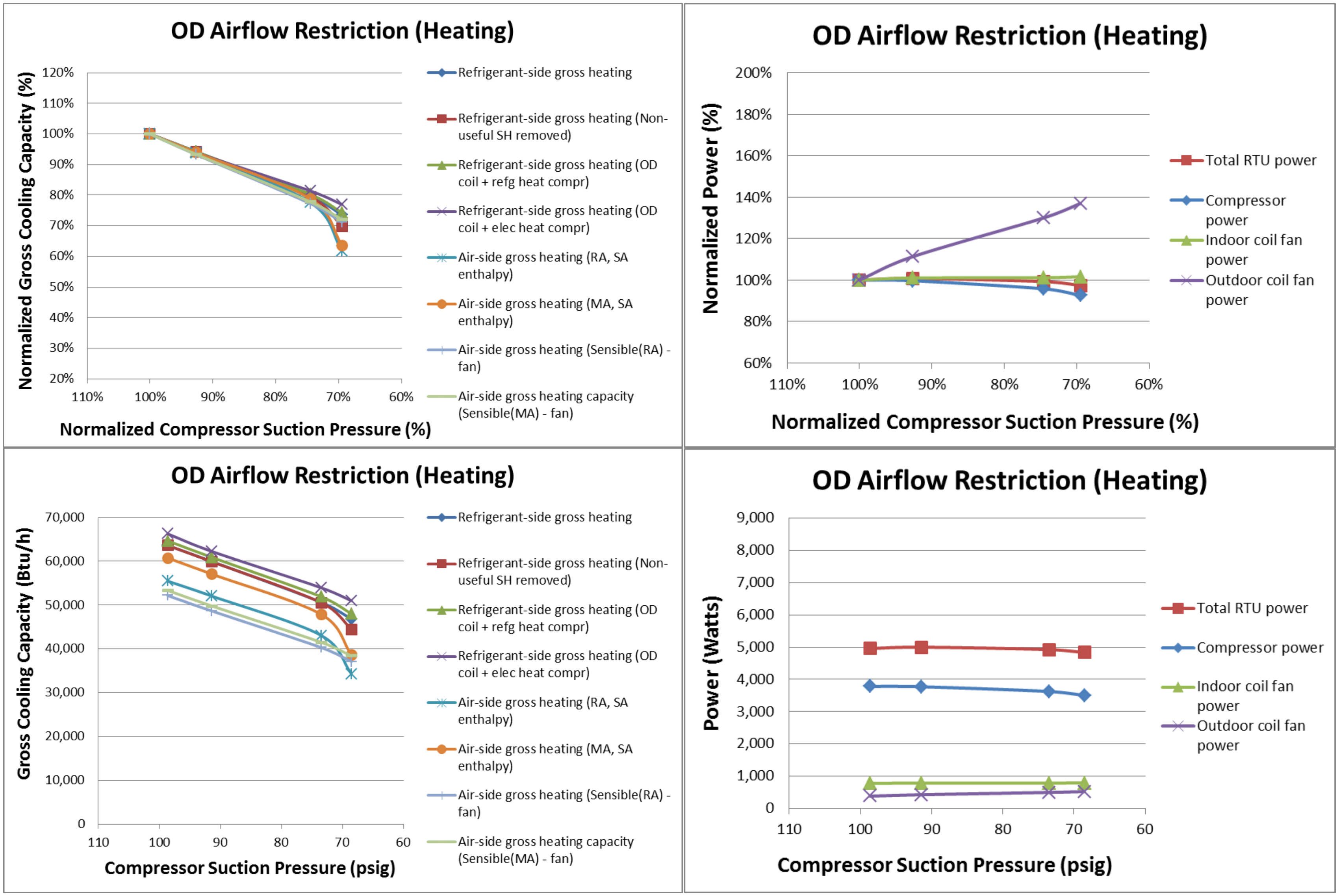


Figure 39. Improper Charge (Heating Mode): Power & Cooling Impacts

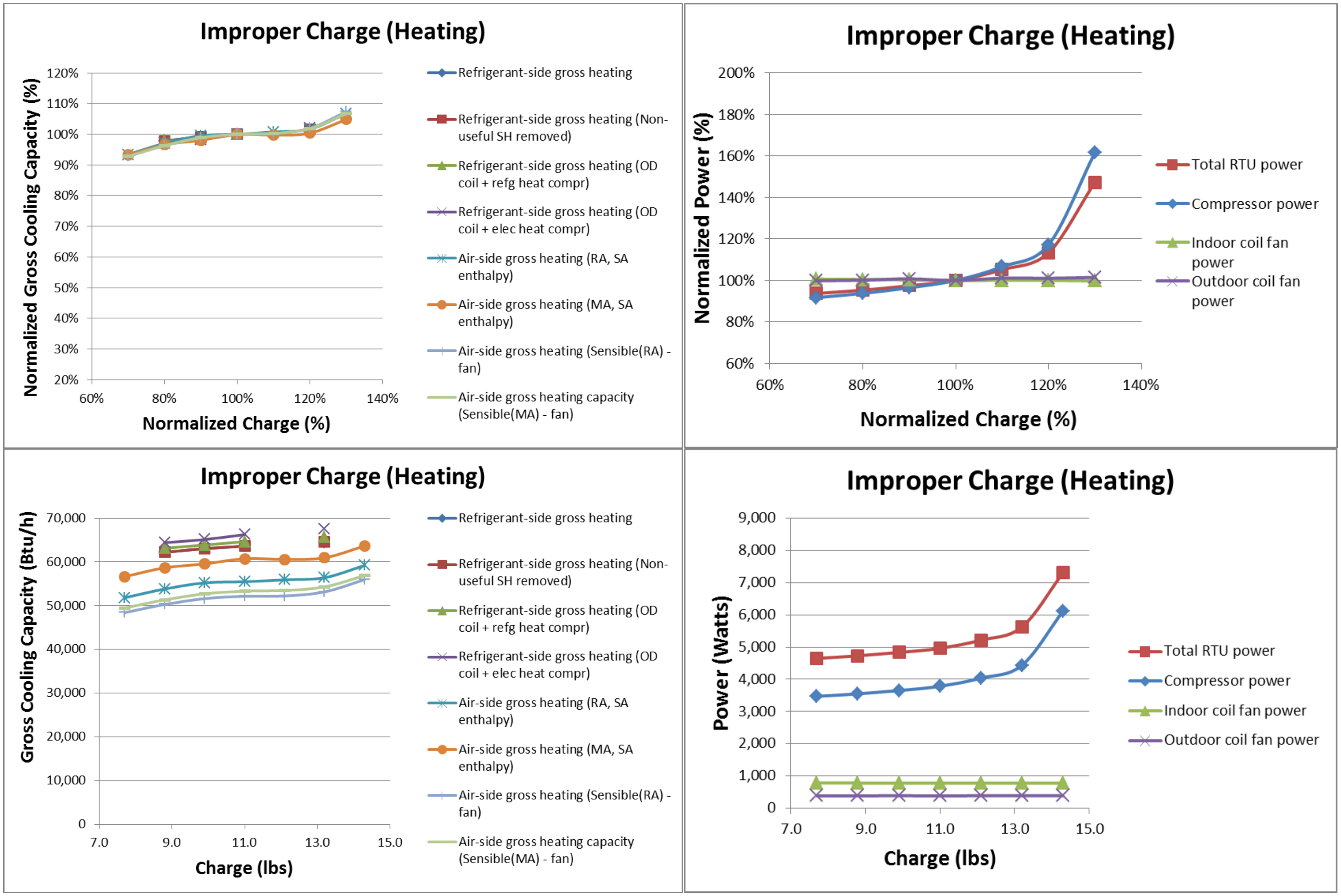


Figure 40. Multiple Faults: Low ID/OD Airflow & Charge (Heating Mode): Power & Cooling Impacts

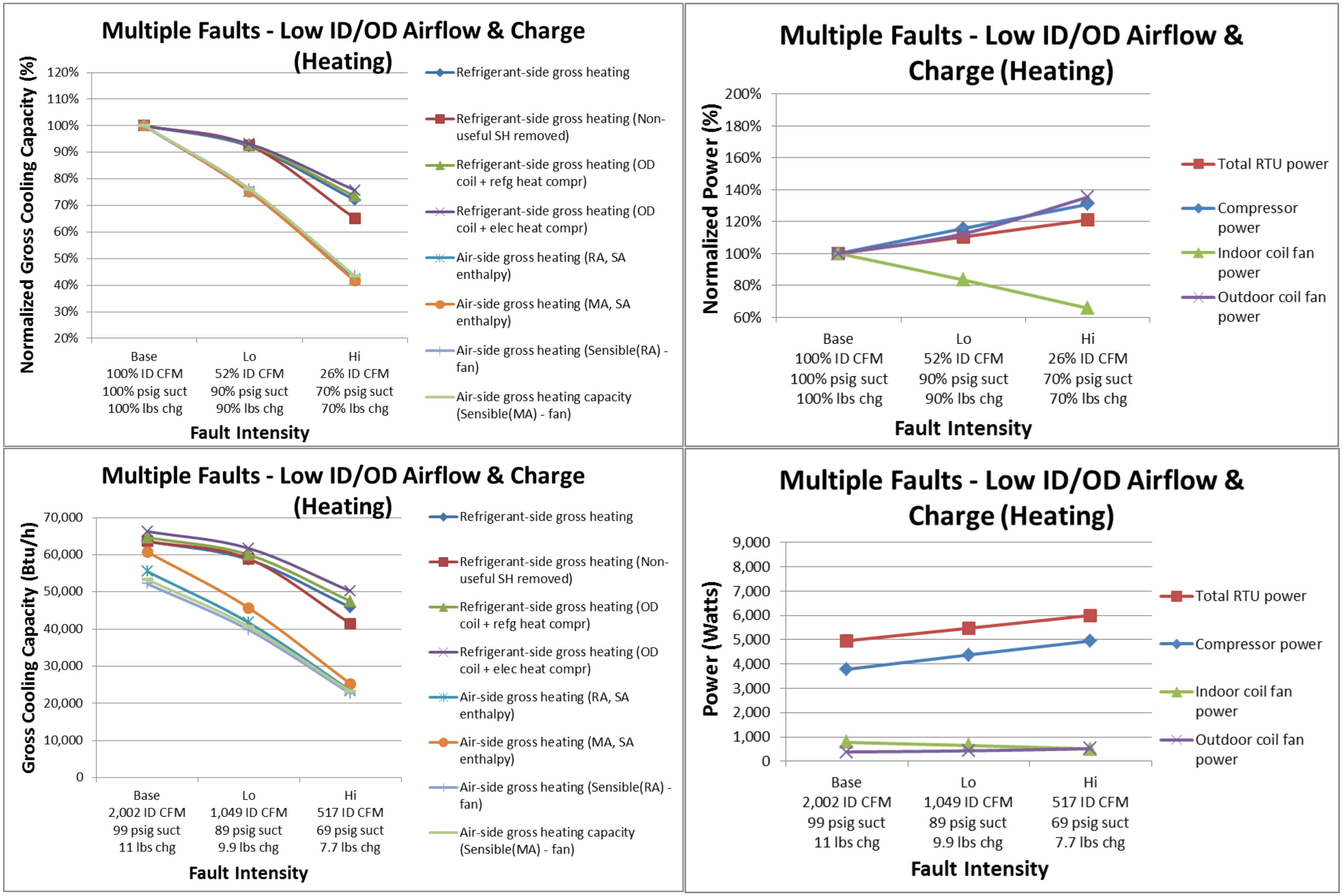


Table 33 – All Cooling Mode Tests, OD ambient of 115F: Power and Cooling Impacts Summary

Tests ->		Base	ID Air Restr	ID Air Restr	Base	OD Air Restr	OD Air Restr	Low Charge	Low Charge	Base	High Charge	High Charge	Base	Low Charge, ID/OD Restr	Low Charge, ID/OD Restr
		1	6	9	1	12	15	21	18	1	24	27	1	30	33
			CFM			PSIG				Lbs					
Fault Increment ->		1,990	1,492	494	487	520	604	7.7	9.9	11.0	12.1	14.3	Base 1,990 ID CFM 487 psig disch 11 lbs chg	Lo 1,492 ID CFM 520 psig disch 9.9 lbs chg	Hi 494 ID CFM 604 psig disch 7.7 lbs chg
		100%	75%	25%	100%	107%	124%	70%	90%	100%	110%	130%	Base 100% ID CFM 100% psig disch 100% lbs chg	Lo 75% ID CFM 107% psig disch 90% lbs chg	Hi 25% ID CFM 124% psig disch 70% lbs chg
Total RTU power	Watts	6,506	6,430	6,129	6,506	6,954	8,131	6,171	6,370	6,506	6,586	6,774	6,506	6,844	7,679
Normalized to baseline	%	100%	99%	94%	100%	107%	125%	95%	98%	100%	101%	104%	100%	105%	118%
Compressor power	Watts	5,346	5,318	5,234	5,346	5,772	6,892	5,014	5,216	5,346	5,435	5,621	5,346	5,698	6,695
Normalized to baseline	%	100%	99%	98%	100%	108%	129%	94%	98%	100%	102%	105%	100%	107%	125%
Indoor coil fan power	Watts	802	762	539	802	805	805	801	798	802	802	802	802	764	536
Normalized to baseline	%	100%	95%	67%	100%	100%	100%	100%	99%	100%	100%	100%	100%	95%	67%
Outdoor coil fan power	Watts	322	322	324	322	342	393	321	321	322	315	316	322	347	409
Normalized to baseline	%	100%	100%	100%	100%	106%	122%	99%	99%	100%	98%	98%	100%	108%	127%
Refrigerant-side gross cooling	Btu/h	53,678	51,489	47,238	53,678	52,710	49,337		52,905	53,678	55,112	55,251	53,678	50,035	38,273
Normalized to baseline	%	100%	96%	88%	100%	98%	92%		99%	100%	103%	103%	100%	93%	71%
Refrigerant-side gross cooling (Non-useful SH removed)	Btu/h	52,067	49,920	46,854	52,067	50,778	47,874		51,102	52,067	53,729	53,780	52,067	48,508	36,927
Normalized to baseline	%	100%	96%	90%	100%	98%	92%		98%	100%	103%	103%	100%	93%	71%
Refrigerant-side gross cooling (heat rej - refg heat compr)	Btu/h	50,990	48,984	43,713	50,990	50,009	47,865		49,170	50,990	52,632	52,728	50,990	46,379	
Normalized to baseline	%	100%	96%	86%	100%	98%	94%		96%	100%	103%	103%	100%	91%	
Refrigerant-side gross cooling (heat rej - elec heat compr)	Btu/h	49,707	47,699	39,719	49,707	48,557	42,840		47,850	49,707	51,177	51,214	49,707	44,947	
Normalized to baseline	%	100%	96%	80%	100%	98%	86%		96%	100%	103%	103%	100%	90%	
Air-side gross cooling (RA, SA enthalpy)	Btu/h	37,621	34,598	19,892	37,621	36,950			35,675	37,621			37,621	30,599	10,133
Normalized to baseline	%	100%	92%	53%	100%	98%			95%	100%			100%	81%	27%
Air-side gross cooling (MA, SA enthalpy)	Btu/h	47,307	43,392	27,055	47,307	46,152	40,860	40,781	45,672	47,307	48,090	48,883	47,307	40,773	20,495
Normalized to baseline	%	100%	92%	57%	100%	98%	86%	86%	97%	100%	102%	103%	100%	86%	43%
Air-side gross cooling (Sensible(RA) + latent(psy-RA) + fan)	Btu/h	36,863	33,608	18,960	36,863	36,252			35,090	36,863			36,863	29,868	9,806
Normalized to baseline	%	100%	91%	51%	100%	98%			95%	100%			100%	81%	27%
Air-side gross cooling (Sensible(RA) + latent(scale) + fan)	Btu/h	38,835	35,886	22,474	38,835	38,785	34,811	33,912	38,912	38,835	41,252	41,425	38,835	32,052	11,666
Normalized to baseline	%	100%	92%	58%	100%	100%	90%	87%	100%	100%	106%	107%	100%	83%	30%
Air-side gross cooling (Sensible(MA) + latent(psy-MA) + fan)	Btu/h	45,583	41,574	25,512	45,583	44,534	39,594	39,391	44,077	45,583	46,191	46,938	45,583	39,067	19,191
Normalized to baseline	%	100%	91%	56%	100%	98%	87%	86%	97%	100%	101%	103%	100%	86%	42%
Air-side gross cooling (Sensible(MA) + latent(scale) + fan)	Btu/h	40,185	37,614	24,592	40,185	40,039	35,889	35,177	40,175	40,185	42,365	42,765	40,185	33,894	13,783
Normalized to baseline	%	100%	94%	61%	100%	100%	89%	88%	100%	100%	105%	106%	100%	84%	34%

Note: some calculations are removed as erroneous because of impacts from mixed phase refrigerant flow due to low charge or bad return air humidity readings.

Table 34 – All Cooling Mode Tests, OD ambient of 95F: Power and Cooling Impacts Summary

Tests ->		Base	ID Air Restr	ID Air Restr	Base	OD Air Restr	OD Air Restr	Low Charge	Low Charge	Base	Hi Charge	Hi Charge	Base	Low chge, ID/OD restr	Low chge, ID/OD restr
		2	7	10	2	13	16	22	19	2	25	28	2	31	34
		CFM			PSIG			Lbs							
Fault Increments ->		1,993	1,493	631	380	450	606	7.7	9.9	11.0	12.1	14.3	Base 1,993 ID CFM 380 psig disch 11 lbs chg	Lo 1,493 ID CFM 450 psig disch 9.9 lbs chg	Hi 631 ID CFM 606 psig disch 7.7 lbs chg
		100%	75%	32%	100%	119%	160%	70%	90%	100%	110%	130%	Base 100% ID CFM 100% psig disch 100% lbs chg	Lo 75% ID CFM 119% psig disch 90% lbs chg	Hi 32% ID CFM 160% psig disch 70% lbs chg
Total RTU power	Watts	5,300	5,250	4,985	5,300	6,137	8,168	5,119	5,240	5,300	5,355	5,470	5,300	6,002	7,487
Normalized to baseline	%	100%	99%	94%	100%	116%	154%	97%	99%	100%	101%	103%	100%	113%	141%
Compressor power	Watts	4,142	4,131	4,064	4,142	4,923	6,902	3,962	4,083	4,142	4,201	4,316	4,142	4,840	6,464
Normalized to baseline	%	100%	100%	98%	100%	119%	167%	96%	99%	100%	101%	104%	100%	117%	156%
Indoor coil fan power	Watts	803	765	566	803	805	804	804	802	803	804	803	803	760	554
Normalized to baseline	%	100%	95%	70%	100%	100%	100%	100%	100%	100%	100%	100%	100%	95%	69%
Outdoor coil fan power	Watts	332	331	332	332	376	419	329	328	332	326	327	332	374	431
Normalized to baseline	%	100%	100%	100%	100%	113%	126%	99%	99%	100%	98%	98%	100%	113%	130%
Refrigerant-side gross cooling	Btu/h	59,712	58,391	49,522	59,712	57,960	55,905		60,023	59,712	61,431	61,656	59,712	57,789	45,594
Normalized to baseline	%	100%	98%	83%	100%	97%	94%		101%	100%	103%	103%	100%	97%	76%
Refrigerant-side gross cooling (Non-useful SH removed)	Btu/h	57,925	56,694	49,181	57,925	57,559	55,243		58,518	57,925	59,636	59,829	57,925	57,403	44,986
Normalized to baseline	%	100%	98%	85%	100%	99%	95%		101%	100%	103%	103%	100%	99%	78%
Refrigerant-side gross cooling (heat rej - refg heat compr)	Btu/h	57,580	56,226	47,605	57,580	56,109	48,727		57,175	57,580	59,013	59,301	57,580	53,124	
Normalized to baseline	%	100%	98%	83%	100%	97%	85%		99%	100%	102%	103%	100%	92%	
Refrigerant-side gross cooling (heat rej - elec heat compr)	Btu/h	56,678	55,327	46,843	56,678	54,934	44,505		56,208	56,678	58,005	58,299	56,678	50,020	
Normalized to baseline	%	100%	98%	83%	100%	97%	79%		99%	100%	102%	103%	100%	88%	
Air-side gross cooling (RA, SA enthalpy)	Btu/h	48,508	44,846	30,831	48,508	46,850		43,083	48,024	48,508	47,623	48,325	48,508	38,514	11,441
Normalized to baseline	%	100%	92%	64%	100%	97%		89%	99%	100%	98%	100%	100%	79%	24%
Air-side gross cooling (MA, SA enthalpy)	Btu/h	53,544	50,084	33,331	53,544	52,197	40,318	49,232	53,384	53,544	54,905	55,737	53,544	43,816	17,706
Normalized to baseline	%	100%	94%	62%	100%	97%	75%	92%	100%	100%	103%	104%	100%	82%	33%
Air-side gross cooling (Sensible(RA) + latent(psy-RA) + fan)	Btu/h	47,137	43,348	29,418	47,137	45,611		42,072	46,790	47,137	46,402	47,092	47,137	37,378	11,198
Normalized to baseline	%	100%	92%	62%	100%	97%		89%	99%	100%	98%	100%	100%	79%	24%
Air-side gross cooling (Sensible(RA) + latent(scale) + fan)	0	49,271	46,696	32,409	49,271	47,354	37,192	45,670	49,875	49,681	52,276	52,326	49,681	40,782	12,852
Normalized to baseline	%	100%	95%	66%	100%	96%	75%	93%	101%	101%	106%	106%	101%	83%	26%
Air-side gross cooling (Sensible(MA) + latent(psy-MA) + fan)	Btu/h	51,598	48,008	31,695	51,598	50,335	39,273	47,518	51,526	51,598	52,831	53,647	51,598	42,095	16,809
Normalized to baseline	%	100%	93%	61%	100%	98%	76%	92%	100%	100%	102%	104%	100%	82%	33%
Air-side gross cooling (Sensible(MA) + latent(scale) + fan)	0	49,218	46,854	33,029	49,218	47,174	36,956	45,592	49,697	49,628	51,973	52,137	49,628	40,935	13,433
Normalized to baseline	%	100%	95%	67%	100%	96%	75%	93%	101%	101%	106%	106%	101%	83%	27%

Note: some calculations are removed as erroneous because of impacts from mixed phase refrigerant flow due to low charge or bad return air humidity readings.

Table 35 – All Cooling Mode Tests, OD ambient of 80F: Power and Cooling Impacts Summary

Tests ->		Base	ID Air Restr	ID Air Restr	Base	OD Air Restr	OD Air Restr	Low Charge	Low Charge	Base	Hi Charge	Hi Charge	Base	Low chge, ID/OD restr	Low chge, ID/OD restr
		3	8	11	3	14	17	23	20	3	26	29	3	32	35
		CFM			PSIG			Lbs							
Fault Increment ->		1,992	1,498	837	311	411	604	7.7	9.9	11.0	12.1	14.3	Base 1,992 ID CFM 311 psig disch 11 lbs chg	Lo 1,498 ID CFM 411 psig disch 9.9 lbs chg	Hi 837 ID CFM 604 psig disch 7.7 lbs chg
		100%	75%	42%	100%	132%	194%	70%	90%	100%	110%	130%	Base 100% ID CFM 100% psig disch 100% lbs chg	Lo 75% ID CFM 132% psig disch 90% lbs chg	Hi 42% ID CFM 194% psig disch 70% lbs chg
Total RTU power	Watts	4,586	4,539	4,318	4,586	5,719	8,200	4,461	4,556	4,586	4,648	4,734	4,586	5,620	7,610
Normalized to baseline	%	100%	99%	94%	100%	125%	179%	97%	99%	100%	101%	103%	100%	123%	166%
Compressor power	Watts	3,422	3,415	3,355	3,422	4,472	6,923	3,298	3,398	3,422	3,489	3,570	3,422	4,422	6,526
Normalized to baseline	%	100%	100%	98%	100%	131%	202%	96%	99%	100%	102%	104%	100%	129%	191%
Indoor coil fan power	Watts	805	767	605	805	806	804	807	803	805	805	809	805	766	600
Normalized to baseline	%	100%	95%	75%	100%	100%	100%	100%	100%	100%	100%	101%	100%	95%	75%
Outdoor coil fan power	Watts	339	338	339	339	411	431	335	336	339	333	332	339	407	444
Normalized to baseline	%	100%	100%	100%	100%	121%	127%	99%	99%	100%	98%	98%	100%	120%	131%
Refrigerant-side gross cooling	Btu/h	63,905	62,346	55,121	63,905	61,608	53,667		64,427	63,905	65,497	65,745	63,905	59,427	47,119
Normalized to baseline	%	100%	98%	86%	100%	96%	84%		101%	100%	102%	103%	100%	93%	74%
Refrigerant-side gross cooling (Non-useful SH removed)	Btu/h	62,157	60,450	53,387	62,157	59,518	52,987		62,573	62,157	63,727	64,099	62,157	58,995	46,482
Normalized to baseline	%	100%	97%	86%	100%	96%	85%		101%	100%	103%	103%	100%	95%	75%
Refrigerant-side gross cooling (heat rej - refg heat compr)	Btu/h	62,011	60,394	53,380	62,011	58,735	48,210		61,877	62,011	63,321	63,668	62,011	55,326	
Normalized to baseline	%	100%	97%	86%	100%	95%	78%		100%	100%	102%	103%	100%	89%	
Refrigerant-side gross cooling (heat rej - elec heat compr)	Btu/h	61,281	59,670	52,664	61,281	57,592	45,071		61,088	61,281	62,520	62,857	61,281	54,377	
Normalized to baseline	%	100%	97%	86%	100%	94%	74%		100%	100%	102%	103%	100%	89%	
Air-side gross cooling (RA, SA enthalpy)	Btu/h	58,190	54,176	43,073	58,190	54,216	39,915	53,376	56,957	58,190	55,949	57,103	58,190	47,152	18,953
Normalized to baseline	%	100%	93%	74%	100%	93%	69%	92%	98%	100%	96%	98%	100%	81%	33%
Air-side gross cooling (MA, SA enthalpy)	Btu/h	58,054	54,162	41,146	58,054	54,598	40,840	53,415	58,440	58,054	58,943	59,381	58,054	47,893	17,818
Normalized to baseline	%	100%	93%	71%	100%	94%	70%	92%	101%	100%	102%	102%	100%	82%	31%
Air-side gross cooling (Sensible(RA) + latent(psy-RA) + fan)	Btu/h	56,180	52,064	41,097	56,180	52,533	39,106	51,699	55,156	56,180	54,292	55,394	56,180	45,428	18,383
Normalized to baseline	%	100%	93%	73%	100%	94%	70%	92%	98%	100%	97%	99%	100%	81%	33%
Air-side gross cooling (Sensible(RA) + latent(scale) + fan)	Btu/h	56,004	53,423	42,753	56,004	53,559	40,941	51,589	57,039	56,004	57,741	55,146	56,004	45,610	17,469
Normalized to baseline	%	100%	95%	76%	100%	96%	73%	92%	102%	100%	103%	98%	100%	81%	31%
Air-side gross cooling (Sensible(MA) + latent(psy-MA) + fan)	Btu/h	54,960	51,155	40,475	54,960	51,265	37,932	50,516	53,909	54,960	52,971	54,199	54,960	44,502	17,648
Normalized to baseline	%	100%	93%	74%	100%	93%	69%	92%	98%	100%	96%	99%	100%	81%	32%
Air-side gross cooling (Sensible(MA) + latent(scale) + fan)	Btu/h	54,785	52,514	42,130	54,785	52,291	39,766	50,406	55,793	54,785	56,421	53,951	54,785	44,684	16,735
Normalized to baseline	%	100%	96%	77%	100%	95%	73%	92%	102%	100%	103%	98%	100%	82%	31%

Note: some calculations are removed as erroneous because of impacts from mixed phase refrigerant flow due to low charge.

Table 36 – Single Fault Heating Mode Tests: Power and Heating Impacts

Tests ->		Base	ID Restr	ID Restr	ID Restr	Base	OD Restr	OD Restr	OD Restr	Low Charge	Low Charge	Low Charge	Base	Hi Charge	Hi Charge	Hi Charge
		4	36	37	38	4	39	40	41	44	43	42	4	45	46	47
		CFM				PSIG				Lbs						
Fault Increment ->		2002	1049	668	517	99	91	73	69	7.7	8.8	9.9	11.0	12.1	13.2	14.3
		100%	52%	33%	26%	100%	93%	74%	69%	70%	80%	90%	100%	110%	120%	130%
Total RTU power	Watts	4,962	5,844	6,846	8,085	4,962	5,001	4,927	4,835	4,652	4,731	4,837	4,962	5,220	5,626	7,311
Normalized to baseline	%	100%	118%	138%	163%	100%	101%	99%	97%	94%	95%	97%	100%	105%	113%	147%
Compressor power	Watts	3,786	4,783	5,889	7,157	3,786	3,774	3,627	3,505	3,474	3,550	3,654	3,786	4,038	4,438	6,120
Normalized to baseline	%	100%	126%	156%	189%	100%	100%	96%	93%	92%	94%	97%	100%	107%	117%	162%
Indoor coil fan power	Watts	778	640	536	503	778	786	787	791	783	782	781	778	779	779	776
Normalized to baseline	%	100%	82%	69%	65%	100%	101%	101%	102%	101%	101%	100%	100%	100%	100%	100%
Outdoor coil fan power	Watts	383	397	396	396	383	426	498	524	382	383	386	383	387	387	388
Normalized to baseline	%	100%	104%	104%	103%	100%	111%	130%	137%	100%	100%	101%	100%	101%	101%	102%
Refrigerant-side gross heating	Btu/h	63,623	61,374	61,250	58,269	63,623	59,962	50,649	46,809		62,248	63,070	63,623		64,481	
Normalized to baseline	%	100%	96%	96%	92%	100%	94%	80%	74%		98%	99%	100%		101%	
Refrigerant-side gross heating (Non-useful SH removed)	Btu/h	63,643	61,670	61,748	58,250	63,643	59,913	50,565	44,492		62,215	63,077	63,643		64,648	
Normalized to baseline	%	100%	97%	97%	92%	100%	94%	79%	70%		98%	99%	100%		102%	
Refrigerant-side gross heating (OD coil + refg heat compr)	Btu/h	64,673	62,597	62,867	58,442	64,673	60,908	51,915	48,010		63,162	63,909	64,673		65,670	
Normalized to baseline	%	100%	97%	97%	90%	100%	94%	80%	74%		98%	99%	100%		102%	
Refrigerant-side gross heating (OD coil + elec heat compr)	Btu/h	66,285	64,440	65,536	66,006	66,285	62,257	53,964	51,013		64,435	65,166	66,285		67,636	
Normalized to baseline	%	100%	97%	99%	100%	100%	94%	81%	77%		97%	98%	100%		102%	
Air-side gross heating (RA, SA enthalpy)	Btu/h	55,503	45,865	36,943	33,107	55,503	52,061	43,089	34,313	51,839	53,849	55,248	55,503	55,939	56,431	59,242
Normalized to baseline	%	100%	83%	67%	60%	100%	94%	78%	62%	93%	97%	100%	100%	101%	102%	107%
Air-side gross heating (MA, SA enthalpy)	Btu/h	60,768	49,636	39,541	34,802	60,768	57,078	47,892	38,686	56,673	58,692	59,582	60,768	60,617	60,982	63,694
Normalized to baseline	%	100%	82%	65%	57%	100%	94%	79%	64%	93%	97%	98%	100%	100%	100%	105%
Air-side gross heating (Sensible(RA) - fan)	Btu/h	52,187	43,654	35,206	31,580	52,187	48,657	40,310	37,129	48,439	50,296	51,636	52,187	52,248	53,187	55,991
Normalized to baseline	%	100%	84%	67%	61%	100%	93%	77%	71%	93%	96%	99%	100%	100%	102%	107%
Air-side gross heating capacity (Sensible(MA) - fan)	Btu/h	53,355	44,447	35,824	31,805	53,355	49,813	41,513	38,436	49,502	51,360	52,738	53,355	53,507	54,328	56,917
Normalized to baseline	%	100%	83%	67%	60%	100%	93%	78%	72%	93%	96%	99%	100%	100%	102%	107%

Note: some calculations are removed as erroneous because of questionable refrigerant mass flow readings.

Table 37 – Multiple Fault Heating Mode Tests: Power and Heating Impacts

Tests ->		Base	Low chg, ID/OD restr	Low chg, ID/OD restr
		4	48	49
Fault Increment ->		Base 2,002 ID CFM 99 psig suct 11 lbs chg	Lo 1,049 ID CFM 89 psig suct 9.9 lbs chg	Hi 517 ID CFM 69 psig suct 7.7 lbs chg
		Base 100% ID CFM 100% psig suct 100% lbs chg	Lo 52% ID CFM 90% psig suct 90% lbs chg	Hi 26% ID CFM 70% psig suct 70% lbs chg
Total RTU power	Watts	4,962	5,476	6,005
Normalized to baseline	%	100%	110%	121%
Compressor power	Watts	3,786	4,378	4,951
Normalized to baseline	%	100%	116%	131%
Indoor coil fan power	Watts	778	649	511
Normalized to baseline	%	100%	83%	66%
Outdoor coil fan power	Watts	383	430	518
Normalized to baseline	%	100%	112%	135%
Refrigerant-side gross heating	Btu/h	63,623	58,707	45,857
Normalized to baseline	%	100%	92%	72%
Refrigerant-side gross heating (Non-useful SH removed)	Btu/h	63,643	58,893	41,470
Normalized to baseline	%	100%	93%	65%
Refrigerant-side gross heating (OD coil + refg heat compr)	Btu/h	64,673	60,006	47,518
Normalized to baseline	%	100%	93%	73%
Refrigerant-side gross heating (OD coil + elec heat compr)	Btu/h	66,285	61,728	50,204
Normalized to baseline	%	100%	93%	76%
Air-side gross heating (RA, SA enthalpy)	Btu/h	55,503	41,708	23,434
Normalized to baseline	%	100%	75%	42%
Air-side gross heating (MA, SA enthalpy)	Btu/h	60,768	45,656	25,273
Normalized to baseline	%	100%	75%	42%
Air-side gross heating (Sensible(RA) - fan)	Btu/h	52,187	39,743	22,642
Normalized to baseline	%	100%	76%	43%
Air-side gross heating capacity (Sensible(MA) - fan)	Btu/h	53,355	40,656	23,154
Normalized to baseline	%	100%	76%	43%

Results: FDD outputs

The economizer FDD outputs explored in this project were binary in nature: either the fault was diagnosed, or it was not. The following were the results of the economizer FDD tests:

- **Economizer stuck open**
  This fault was considered correctly diagnosed; "Damper is stuck" was indicated. A delay of roughly 3 minutes was needed between the fault occurrence, and the registering of the fault.
- **Economizer stuck at minimum position**
  This fault was considered correctly diagnosed; "Damper is stuck" was indicated. A delay of roughly 3 minutes was needed between the fault occurrence, and the registering of the fault.
- **Bad/unplugged actuator**
  This fault was correctly diagnosed for the four electrical connections that were disconnected separately. For two connections, faults registered instantly ("damper pos value missing"), for the other two connections, a call for damper movement was needed, where a delay of roughly 3 minutes was needed between the fault occurrence, and the registering of the fault ("damper is stuck").
- **Sensor failure**
  Both outside air and supply air temperature sensor faults were instantly and correctly diagnosed.
- **Actuator mechanically disconnected**
  No fault was indicated. This fault seemed to result in movement of the actuator to a correct position while the damper did not move; there did not seem to be a method to diagnose the position of the damper.

In order to analyze FDD for steady-state heating and cooling performance tests, non-binary impacts are present, and thus a more sophisticated analysis method is needed. A fault threshold must be established to determine what can be considered a fault scenario and what a no-fault scenario is. Establishing a general target is necessary, but cannot resolve the natural variation in the unique economic impacts from one end user to the next; fixing a fault could make more financial sense for one end user vs another. The fault threshold chosen for this analysis is:

- Gross cooling/heating capacity impacts (adjusted for ID/OD conditions, all of the air-side and refrigerant-side methods considered) are greater than 10%.
- Total RTU power impacts (adjusted for ID/OD conditions) are greater than 10%.
- Total charge is over 10% of the baseline value.

There is little consistency in the functionality witnessed in the FDD technologies selected for this study. The following six potential outputs are generalized for FDD analysis purposes[9],[10]:

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[9] Jim Braun, (2012). A Method for Evaluating Diagnostic Protocols for Packaged Air Conditioning Equipment. http://newbuildings.org/sites/default/files/FDD_Evaluator_Report_withAppendices.pdf

- **No response**: The FDD doesn't give a response for the given operating condition.
- **Correct**: The operating condition, whether faulted or un-faulted, is correctly identified by the FDD.
- **False alarm**: No significant fault is present, but the FDD indicates the presence of a fault.
- **Misdiagnosis**: A significant fault is present, but the FDD misdiagnoses the type of fault.
- **Missed Detection**: A significant fault is present, but the FDD indicates that no fault is present
- **No Diagnosis**: A significant fault is present, and the FDD detects a fault, but doesn't give a diagnosis.

For the purposes of this study, which covers both single and multiple fault scenarios, the following logic is adopted and illustrated in Figure 41 below. The focus of this analysis is centered on analyzing diagnostics outputs. Messages geared towards symptom detection are not analyzed. For example, if the message indicates a parameter like superheat, is out of the expected range, but gives no diagnosis/multiple possible diagnoses, those messages are not analyzed.

FDD may have the capability to output multiple simultaneous messages when subjected to one test scenario. In this case, each message is analyzed separately, and contributes to the tally for the FDD unit. In this way, an FDD unit may have simultaneous outputs that may or may not conflict; for example, an FDD unit could output a message that is considered a correct diagnosis and one that is a misdiagnosis; both a correct diagnosis and misdiagnosis are tallied for the FDD unit for that given test.

Table 38 summarizes the FDD analysis for FDD units 1 through 3 and the RTU charge protocol, for all cooling mode tests; Figure 42 illustrates the output rate and output count. Output rate is defined as the output count for a given category, divided by the total number of outputs. In this manner, we get a high level view of what responses were observed for all single and multiple fault tests, and baseline no-fault tests. Table 39 and Figure 43 frame the analysis to focus on only the outputs associated with baseline no-fault tests. Table 40 and Figure 44 frame the analysis to focus on only the outputs associated with single fault tests (no baseline or multiple).

For a few tests at the hot/dry OD ambient condition of 115F, the outdoor temperature measurements slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F. For select OD restriction tests, unit 1 & 3 required overrides of high pressure readings to their max values of 555 psig and 600 psig, respectively.

[10] Jim Braun, David Yuill. http://www.sciencedirect.com/science/article/pii/S1359431116310638

Figure 41. FDD Outputs Analysis Flowchart

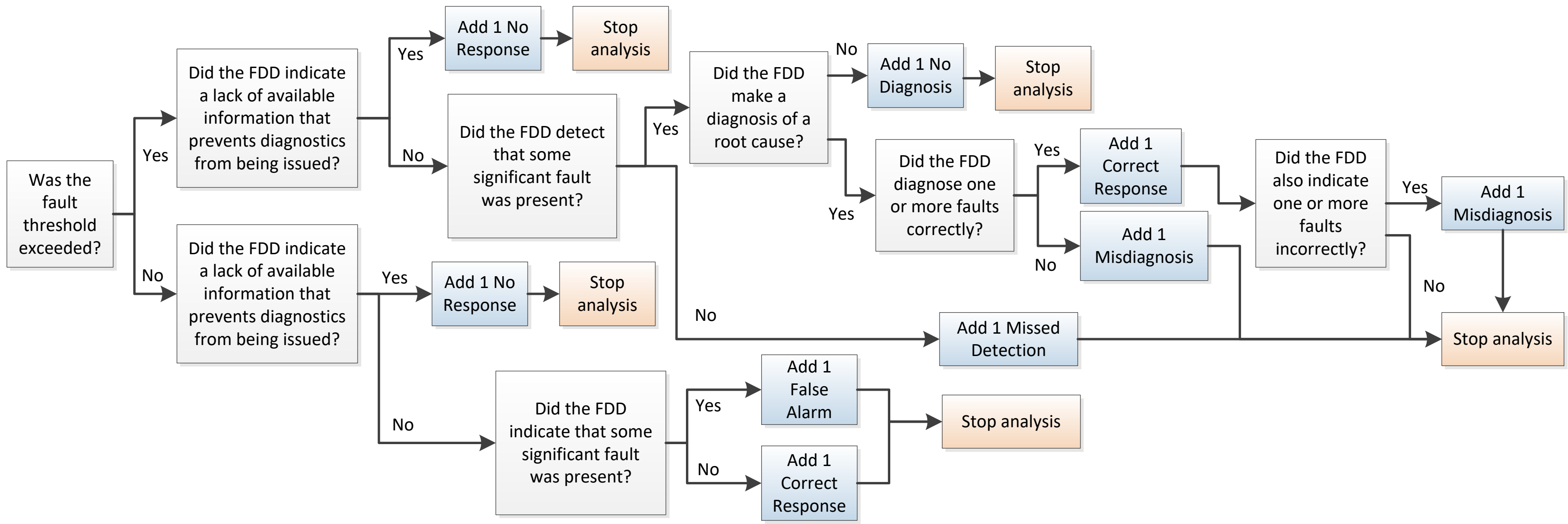

Figure 42. FDD Outputs: All Tests, Cooling Mode

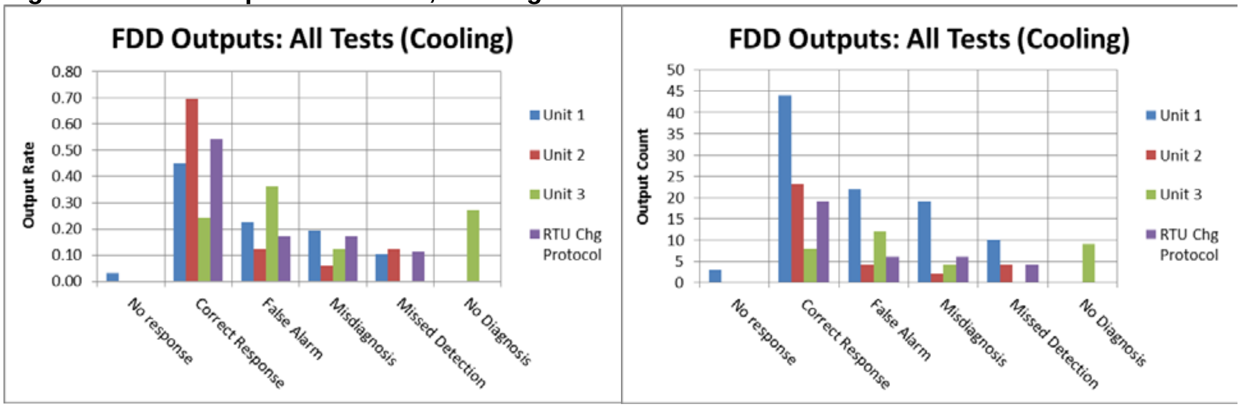

Table 38 – FDD Outputs: All Tests, Cooling Mode

Description	FDD Test Unit	Number of Tests	Tests that Exceed Fault Threshold	Sum of Total Outputs	Output Category	Output Rate	Output Count
All Cooling Mode Tests	Unit 1	33	19	98	No response	0.03	3
					Correct Response	0.45	44
					False Alarm	0.22	22
					Misdiagnosis	0.19	19
					Missed Detection	0.10	10
					No Diagnosis	0.00	0
	Unit 2			33	No response	0.00	0
					Correct Response	0.70	23
					False Alarm	0.12	4
					Misdiagnosis	0.06	2
					Missed Detection	0.12	4
					No Diagnosis	0.00	0
	Unit 3			33	No response	0.00	0
					Correct Response	0.24	8
					False Alarm	0.36	12
					Misdiagnosis	0.12	4
					Missed Detection	0.00	0
					No Diagnosis	0.27	9
	RTU Chg Protocol			35	No response	0.00	0
					Correct Response	0.54	19
					False Alarm	0.17	6
					Misdiagnosis	0.17	6
					Missed Detection	0.11	4
					No Diagnosis	0.00	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge.

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

For select OD restriction tests, unit 1 & 3 required overrides of high pressure readings to their max values.

Figure 43. FDD Outputs: Baseline Tests, Cooling Mode

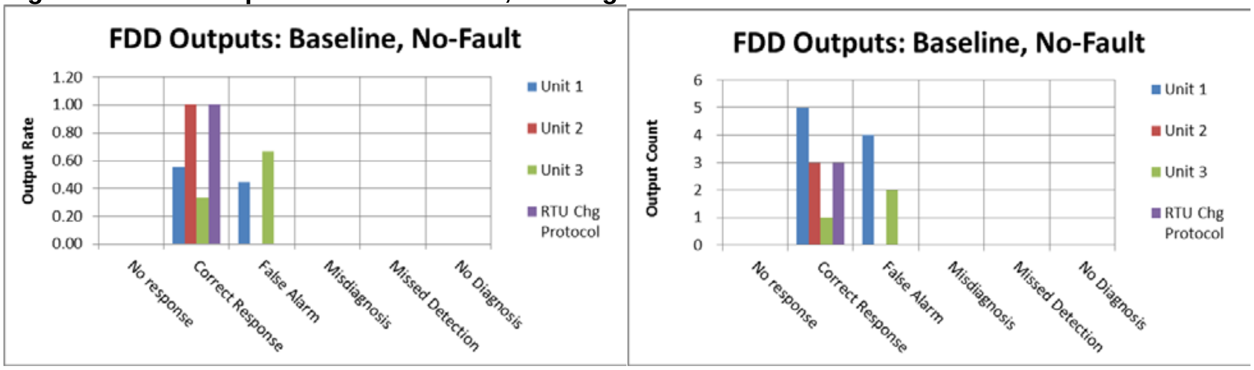

Table 39 – FDD Outputs: Baseline Tests, Cooling Mode

					Test ID ->	Test 1	Test 2	Test 3
						ID/OD Test Chamber Conditions		
Scenario	FDD Test Unit	Number of Tests	Output	Output Rate	Output Count	Hot & Dry 75F/62.5F ID 115F OD	High 75F/62.5F ID 95F OD	Mild 75F/62.5F ID 80F OD
Baseline	Unit 1	3	No response	**0.00**	**0**	0	0	0
			Correct Response	**0.56**	**5**	1	2	2
			False Alarm	**0.44**	**4**	2	1	1
			Misdiagnosis	**0.00**	**0**	0	0	0
			Missed Detection	**0.00**	**0**	0	0	0
			No Diagnosis	**0.00**	**0**	0	0	0
	Unit 2	3	No response	**0.00**	**0**	0	0	0
			Correct Response	**1.00**	**3**	1	1	1
			False Alarm	**0.00**	**0**	0	0	0
			Misdiagnosis	**0.00**	**0**	0	0	0
			Missed Detection	**0.00**	**0**	0	0	0
			No Diagnosis	**0.00**	**0**	0	0	0
	Unit 3	3	No response	**0.00**	**0**	0	0	0
			Correct Response	**0.33**	**1**	0	0	1
			False Alarm	**0.67**	**2**	1	1	0
			Misdiagnosis	**0.00**	**0**	0	0	0
			Missed Detection	**0.00**	**0**	0	0	0
			No Diagnosis	**0.00**	**0**	0	0	0
	RTU Chg Protocol	3	No response	**0.00**	**0**	0	0	0
			Correct Response	**1.00**	**3**	1	1	1
			False Alarm	**0.00**	**0**	0	0	0
			Misdiagnosis	**0.00**	**0**	0	0	0
			Missed Detection	**0.00**	**0**	0	0	0
			No Diagnosis	**0.00**	**0**	0	0	0

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

Figure 44. FDD Outputs: Single Fault Tests, Cooling Mode

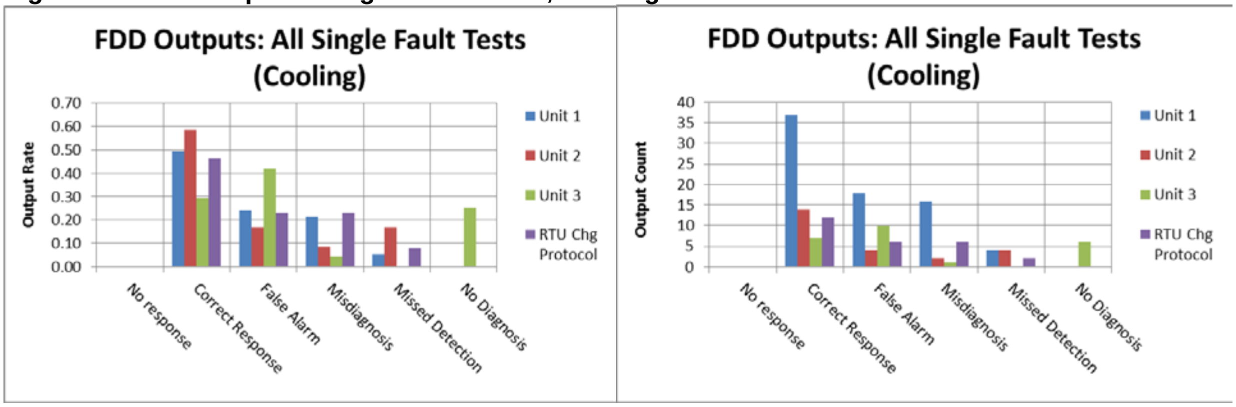

Table 40 – FDD Outputs: Single Fault Tests, Cooling Mode

Description	FDD Test Unit	Number of Tests	Tests that Exceed Fault Threshold	Sum of Total Outputs	Output	Output Rate	Output Count
All Single Fault Cooling Mode Tests	Unit 1	24	13	75	No response	0.00	0
					Correct Response	0.49	37
					False Alarm	0.24	18
					Misdiagnosis	0.21	16
					Missed Detection	0.05	4
					No Diagnosis	0.00	0
	Unit 2			24	No response	0.00	0
					Correct Response	0.58	14
					False Alarm	0.17	4
					Misdiagnosis	0.08	2
					Missed Detection	0.17	4
					No Diagnosis	0.00	0
	Unit 3			24	No response	0.00	0
					Correct Response	0.29	7
					False Alarm	0.42	10
					Misdiagnosis	0.04	1
					Missed Detection	0.00	0
					No Diagnosis	0.25	6
	RTU Chg Protocol			26	No response	0.00	0
					Correct Response	0.46	12
					False Alarm	0.23	6
					Misdiagnosis	0.23	6
					Missed Detection	0.08	2
					No Diagnosis	0.00	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge.

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

For select OD restriction tests, unit 1 & 3 required overrides of high pressure readings to their max values.

Figure 45. FDD Outputs: Multiple Fault Tests, Cooling Mode

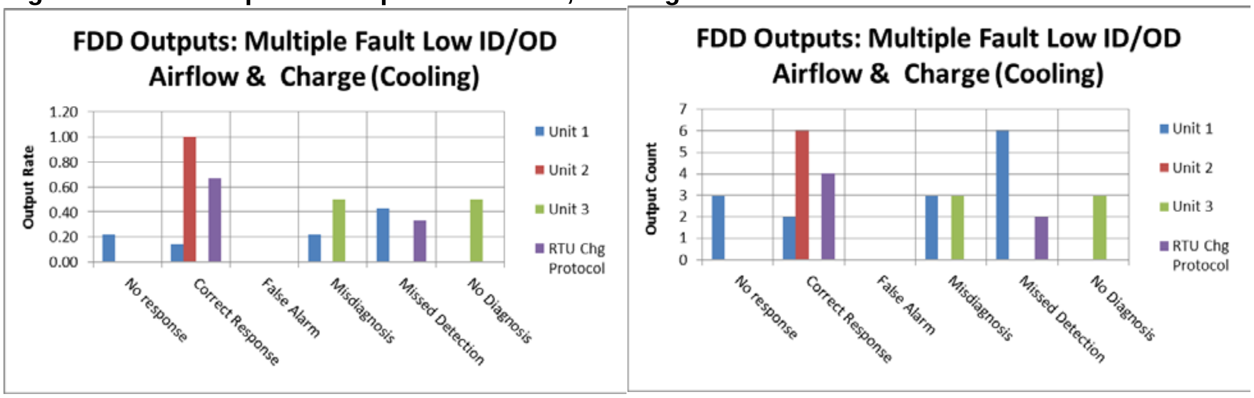

Table 41 – FDD Outputs: Multiple Fault Tests, Cooling Mode

							Test ID ->	30	33	31	34	32	35
							Fault Severity ->	Lo	Hi	Lo	Hi	Lo	Hi
							Fault Threshold Exceeded?	Yes	Yes	Yes	Yes	Yes	Yes
								ID/OD Test Chamber Conditions					
Description	**FDD Test Unit**	**Number of Tests**	**Tests that Exceed Threshold**	**Sum of Total Outputs**	**Output**	**Output Rate**	**Output Count**	**Hot & Dry 80F/67F ID 115F OD**		**AHRI 80F/67F ID 95F OD**		**Mild 80F/67F ID 80F OD**	
Cooling Mode Multiple Fault Tests: Low ID/OD Airflow and Charge	Unit 1	6	6	14	No response	**0.21**	**3**	0	1	0	1	0	1
					Correct Response	**0.14**	**2**	1	0	1	0	0	0
					False Alarm	**0.00**	**0**	0	0	0	0	0	0
					Misdiagnosis	**0.21**	**3**	1	0	1	0	1	0
					Missed Detection	**0.43**	**6**	1	0	2	0	3	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0
	Unit 2			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**1.00**	**6**	1	1	1	1	1	1
					False Alarm	**0.00**	**0**	0	0	0	0	0	0
					Misdiagnosis	**0.00**	**0**	0	0	0	0	0	0
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0
	Unit 3			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.00**	**0**	0	0	0	0	0	0
					False Alarm	**0.00**	**0**	0	0	0	0	0	0
					Misdiagnosis	**0.50**	**3**	0	0	1	1	0	1
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.50**	**3**	1	1	0	0	1	0
	RTU Chg Protocol			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.67**	**4**	0	1	1	1	0	1
					False Alarm	**0.00**	**0**	0	0	0	0	0	0
					Misdiagnosis	**0.00**	**0**	0	0	0	0	0	0
					Missed Detection	**0.33**	**2**	1	0	0	0	1	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge.

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

For select OD restriction tests, unit 1 & 3 required overrides of high pressure readings to their max values.

Figure 46. FDD Outputs: ID Airflow Restriction Fault Tests, Cooling Mode

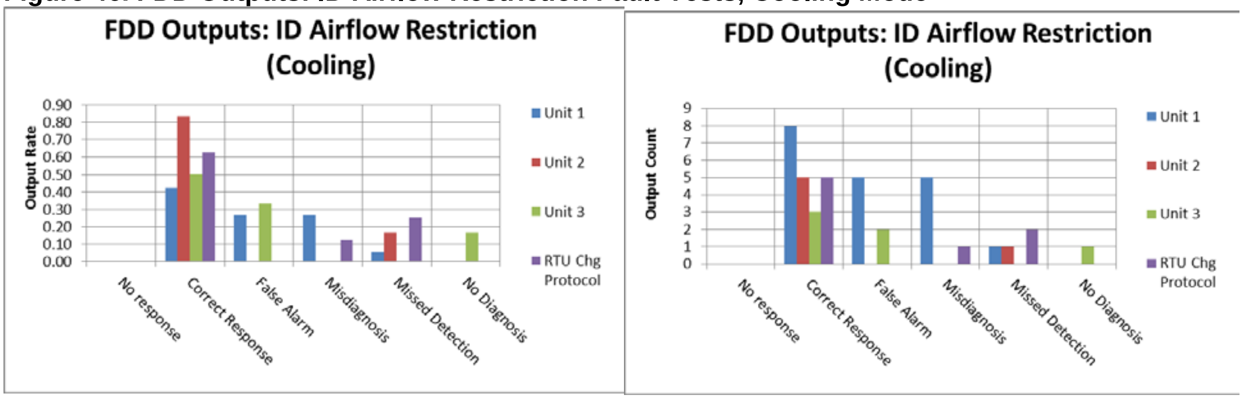

Table 42 – FDD Outputs: ID Airflow Restriction Fault Tests, Cooling Mode

							Test ID ->	6	9	7	10	8	11
							Fault Severity ->	Lo	Hi	Lo	Hi	Lo	Hi
							Fault Threshold Exceeded?	No	Yes	No	Yes	No	Yes
								ID/OD Test Chamber Conditions					
Description	FDD Test Unit	Number of Tests	Tests that Exceed Threshold	Sum of Total Outputs	Output	Output Rate	Output Count	Hot & Dry 80F/67F ID 115F OD		AHRI 80F/67F ID 95F OD		Mild 80F/67F ID 80F OD	
ID Airflow Restriction	Unit 1	6	3	19	No response	0.00	0	0	0	0	0	0	0
					Correct Response	0.42	8	1	0	2	2	1	2
					False Alarm	0.26	5	2	0	1	0	2	0
					Misdiagnosis	0.26	5	0	3	0	1	0	1
					Missed Detection	0.05	1	0	1	0	0	0	0
					No Diagnosis	0.00	0	0	0	0	0	0	0
	Unit 2			6	No response	0.00	0	0	0	0	0	0	0
					Correct Response	0.83	5	1	1	1	1	1	0
					False Alarm	0.00	0	0	0	0	0	0	0
					Misdiagnosis	0.00	0	0	0	0	0	0	0
					Missed Detection	0.17	1	0	0	0	0	0	1
					No Diagnosis	0.00	0	0	0	0	0	0	0
	Unit 3			6	No response	0.00	0	0	0	0	0	0	0
					Correct Response	0.50	3	0	0	1	1	0	1
					False Alarm	0.33	2	1	0	0	0	1	0
					Misdiagnosis	0.00	0	0	0	0	0	0	0
					Missed Detection	0.00	0	0	0	0	0	0	0
					No Diagnosis	0.17	1	0	1	0	0	0	0
	RTU Chg Protocol			8	No response	0.00	0	0	0	0	0	0	0
					Correct Response	0.63	5	1	0	1	1	1	1
					False Alarm	0.00	0	0	0	0	0	0	0
					Misdiagnosis	0.13	1	0	1	0	0	0	0
					Missed Detection	0.25	2	0	0	0	1	0	1
					No Diagnosis	0.00	0	0	0	0	0	0	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

Figure 47. FDD Outputs: OD Airflow Restriction Fault Tests, Cooling Mode

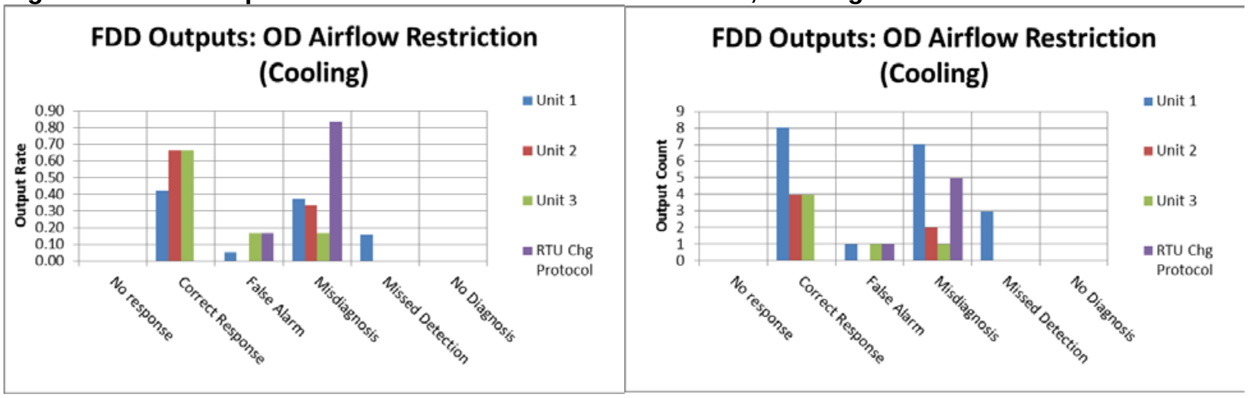

Table 43 – FDD Outputs: OD Airflow Restriction Fault Tests, Cooling Mode

							Test ID ->	12	15	13	16	14	17
							Fault Severity ->	Lo	Hi	Lo	Hi	Lo	Hi
							Fault Threshold Exceeded?	No	Yes	Yes	Yes	Yes	Yes
								ID/OD Test Chamber Conditions					
Description	FDD Test Unit	Number of Tests	Tests that Exceed Threshold	Sum of Total Outputs	Output	Output Rate	Output Count	Hot & Dry 80F/67F ID 115F OD		AHRI 80F/67F ID 95F OD		Mild 80F/67F ID 80F OD	
OD Airflow Restriction	Unit 1	6	5	19	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.42**	**8**	2	0	1	2	1	2
					False Alarm	**0.05**	**1**	1	0	0	0	0	0
					Misdiagnosis	**0.37**	**7**	0	2	1	2	1	1
					Missed Detection	**0.16**	**3**	0	1	1	0	1	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0
	Unit 2			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.67**	**4**	1	1	1	1	0	0
					False Alarm	**0.00**	**0**	0	0	0	0	0	0
					Misdiagnosis	**0.33**	**2**	0	0	0	0	1	1
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0
	Unit 3			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.67**	**4**	0	1	1	0	1	1
					False Alarm	**0.17**	**1**	1	0	0	0	0	0
					Misdiagnosis	**0.17**	**1**	0	0	0	1	0	0
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0
	RTU Chg Protocol			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.00**	**0**	0	0	0	0	0	0
					False Alarm	**0.17**	**1**	1	0	0	0	0	0
					Misdiagnosis	**0.83**	**5**	0	1	1	1	1	1
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge.

For select OD restriction tests, unit 1 & 3 required overrides of high pressure readings to their max values.

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

Figure 48. FDD Outputs: Low Charge Fault Tests, Cooling Mode

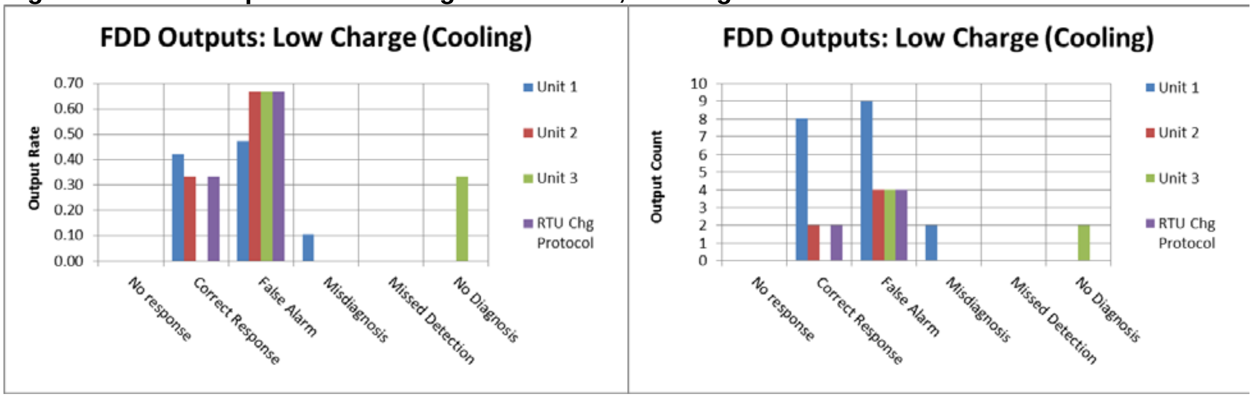

Table 44 – FDD Outputs: Low Charge Fault Tests, Cooling Mode

							Test ID ->	18	21	19	22	20	23
							Fault Severity ->	Lo	Hi	Lo	Hi	Lo	Hi
							Fault Threshold Exceeded?	No	Yes	No	Yes	No	Yes
								ID/OD Test Chamber Conditions					
Description	FDD Test Unit	Number of Tests	Tests that Exceed Threshold	Sum of Total Outputs	Output	Output Rate	Output Count	Hot & Dry 80F/67F ID 115F OD		AHRI 80F/67F ID 95F OD		Mild 80F/67F ID 80F OD	
Low Charge	Unit 1	6	3	19	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.42**	**8**	0	2	1	3	1	1
					False Alarm	**0.47**	**9**	3	0	2	0	2	2
					Misdiagnosis	**0.11**	**2**	0	2	0	0	0	0
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0
	Unit 2			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.33**	**2**	0	1	0	1	0	0
					False Alarm	**0.67**	**4**	1	0	1	0	1	1
					Misdiagnosis	**0.00**	**0**	0	0	0	0	0	0
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0
	Unit 3			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.00**	**0**	0	0	0	0	0	0
					False Alarm	**0.67**	**4**	1	0	1	0	1	1
					Misdiagnosis	**0.00**	**0**	0	0	0	0	0	0
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.33**	**2**	0	1	0	1	0	0
	RTU Chg Protocol			6	No response	**0.00**	**0**	0	0	0	0	0	0
					Correct Response	**0.33**	**2**	0	1	0	1	0	0
					False Alarm	**0.67**	**4**	1	0	1	0	1	1
					Misdiagnosis	**0.00**	**0**	0	0	0	0	0	0
					Missed Detection	**0.00**	**0**	0	0	0	0	0	0
					No Diagnosis	**0.00**	**0**	0	0	0	0	0	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge.

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

Figure 49. FDD Outputs: High Charge Fault Tests, Cooling Mode

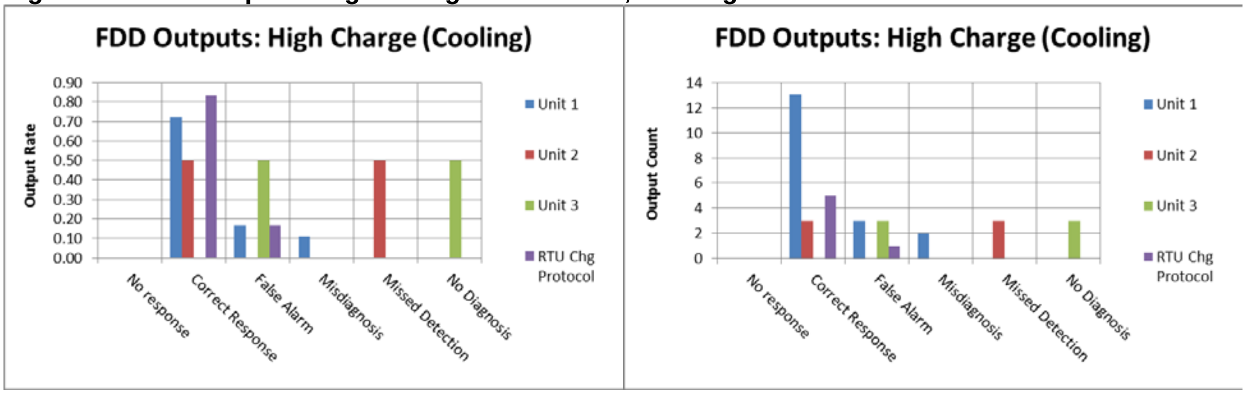

Table 45 – FDD Outputs: High Charge Fault Tests, Cooling Mode

							Test ID ->	24	27	25	28	26	29
							Fault Severity ->	Lo	Hi	Lo	Hi	Lo	Hi
							Fault Threshold Exceeded?	No	Yes	No	Yes	No	Yes
								ID/OD Test Chamber Conditions					
Description	FDD Test Unit	Number of Tests	Tests that Exceed Threshold	Sum of Total Outputs	Output	Output Rate	Output Count	Hot & Dry 80F/67F ID 115F OD		AHRI 80F/67F ID 95F OD		Mild 80F/67F ID 80F OD	
High Charge	Unit 1	6	3	18	No response	0.00	0	0	0	0	0	0	0
					Correct Response	0.72	13	2	2	2	3	2	2
					False Alarm	0.17	3	1	0	1	0	1	0
					Misdiagnosis	0.11	2	0	1	0	0	0	1
					Missed Detection	0.00	0	0	0	0	0	0	0
					No Diagnosis	0.00	0	0	0	0	0	0	0
	Unit 2			6	No response	0.00	0	0	0	0	0	0	0
					Correct Response	0.50	3	1	0	1	0	1	0
					False Alarm	0.00	0	0	0	0	0	0	0
					Misdiagnosis	0.00	0	0	0	0	0	0	0
					Missed Detection	0.50	3	0	1	0	1	0	1
					No Diagnosis	0.00	0	0	0	0	0	0	0
	Unit 3			6	No response	0.00	0	0	0	-	0	0	0
					Correct Response	0.00	0	0	0	0	0	0	0
					False Alarm	0.50	3	1	0	1	0	1	0
					Misdiagnosis	0.00	0	0	0	0	0	0	0
					Missed Detection	0.00	0	0	0	0	0	0	0
					No Diagnosis	0.50	3	0	1	0	1	0	1
	RTU Chg Protocol			6	No response	0.00	0	0	0	0	0	0	0
					Correct Response	0.83	5	0	1	1	1	1	1
					False Alarm	0.17	1	1	0	0	0	0	0
					Misdiagnosis	0.00	0	0	0	0	0	0	0
					Missed Detection	0.00	0	0	0	0	0	0	0
					No Diagnosis	0.00	0	0	0	0	0	0	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge.

For select tests at OD 115F, the OD temps slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.

Figure 50. FDD Outputs: All Tests, Heating Mode

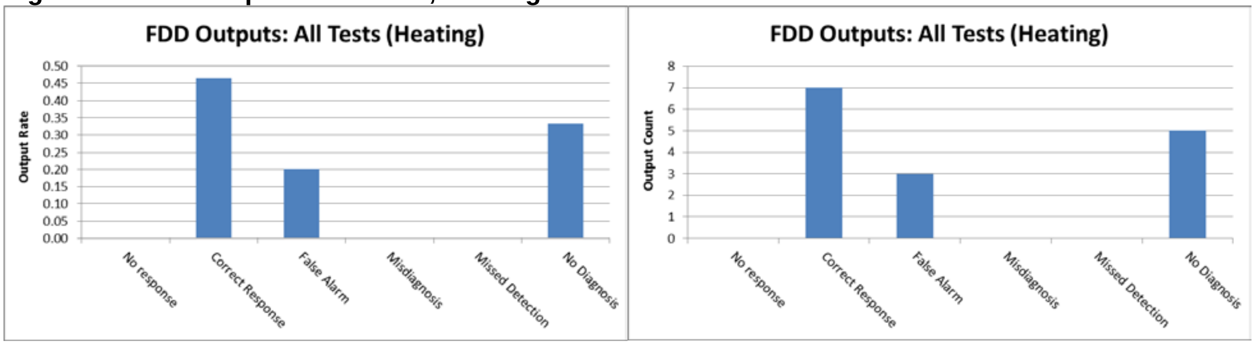

Table 46 – FDD Outputs: All Tests, Heating Mode

Description	FDD Test Unit	Number of Tests	Tests that Exceed Fault Threshold	Sum of Total Outputs	Output	Output Rate	Output Count
All Heating Mode Tests	Unit X	15	10	15	No response	0.00	0
					Correct Response	0.47	7
					False Alarm	0.20	3
					Misdiagnosis	0.00	0
					Missed Detection	0.00	0
					No Diagnosis	0.33	5

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge

Figure 51. FDD Outputs: Baseline Tests, Heating Mode

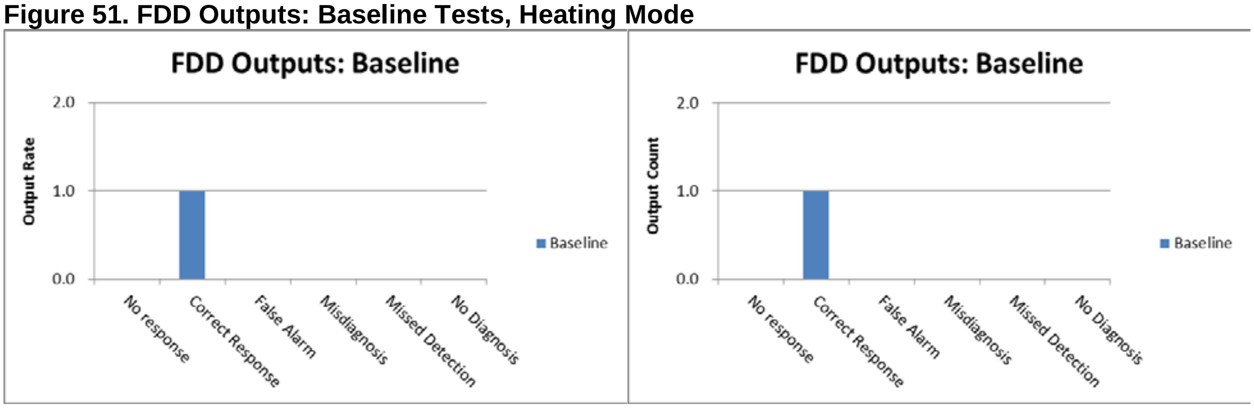

Table 47 – FDD Outputs: Baseline Tests, Heating Mode

					Test ID ->	Test 4
						ID/OD Test Chamber Conditions
Scenario	FDD Test Unit	Number of Tests	Output	Output Rate	Output Count	70F ID 47F/43F OD
Baseline	Unit X	1	No response	0.00	0	0
			Correct Response	1.00	1	1
			False Alarm	0.00	0	0
			Misdiagnosis	0.00	0	0
			Missed Detection	0.00	0	0
			No Diagnosis	0.00	0	0

Figure 52. FDD Outputs: All Single Fault Tests, Heating Mode

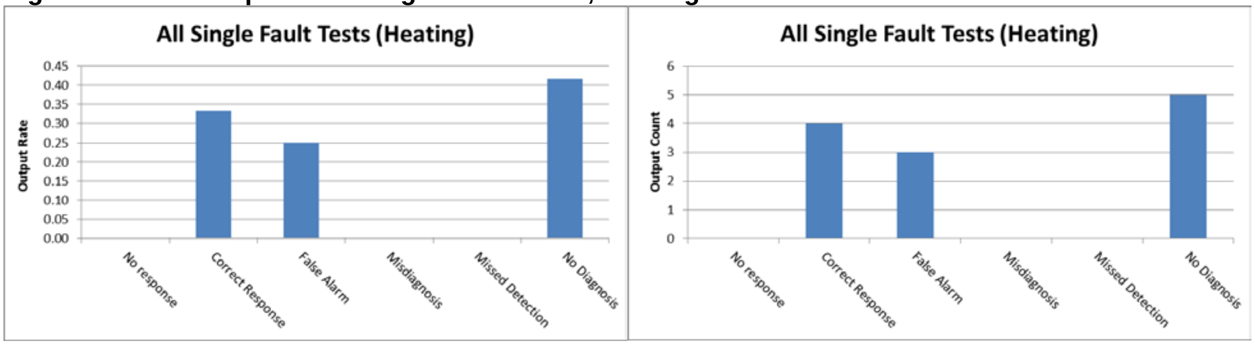

Table 48 – FDD Outputs: All Single Fault Tests, Heating Mode

Description	FDD Test Unit	Number of Tests	Tests that Exceed Fault Threshold	Sum of Total Outputs	Output	Output Rate	Output Count
Heating Mode Single Fault Tests	Unit X	12	8	12	No response	**0.00**	**0**
					Correct Response	**0.33**	**4**
					False Alarm	**0.25**	**3**
					Misdiagnosis	**0.00**	**0**
					Missed Detection	**0.00**	**0**
					No Diagnosis	**0.42**	**5**

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge

Figure 53. FDD Outputs: Multiple Fault Tests, Heating Mode

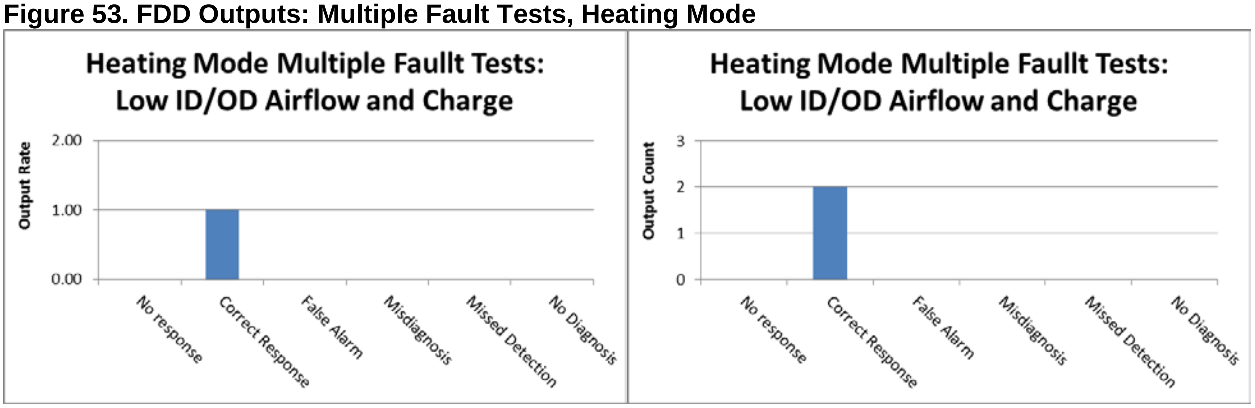

Table 49 – FDD Outputs: Multiple Fault Tests, Heating Mode

						Test ID ->	48	49
						Fault Severity ->	Lo	Hi
						Fault Threshold Exceeded?	Yes	Yes
Fault	**FDD Test Unit**	**Number of Tests**	**Tests that Exceed Fault Threshold**	**Output**	**Output Rate**	**Output Count**	**Mild 80F/67F ID 80F OD**	
Heating Mode Multiple Faullt Tests: Low ID/OD Airflow and Charge	Unit X	2	2	No response	**0.00**	**0**	0	0
				Correct Response	**1.00**	**2**	1	1
				False Alarm	**0.00**	**0**	0	0
				Misdiagnosis	**0.00**	**0**	0	0
				Missed Detection	**0.00**	**0**	0	0
				No Diagnosis	**0.00**	**0**	0	0

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge

Figure 54. FDD Outputs: Single-Fault ID Airflow Restriction & Single-Fault OD Airflow Restriction, Heating Mode

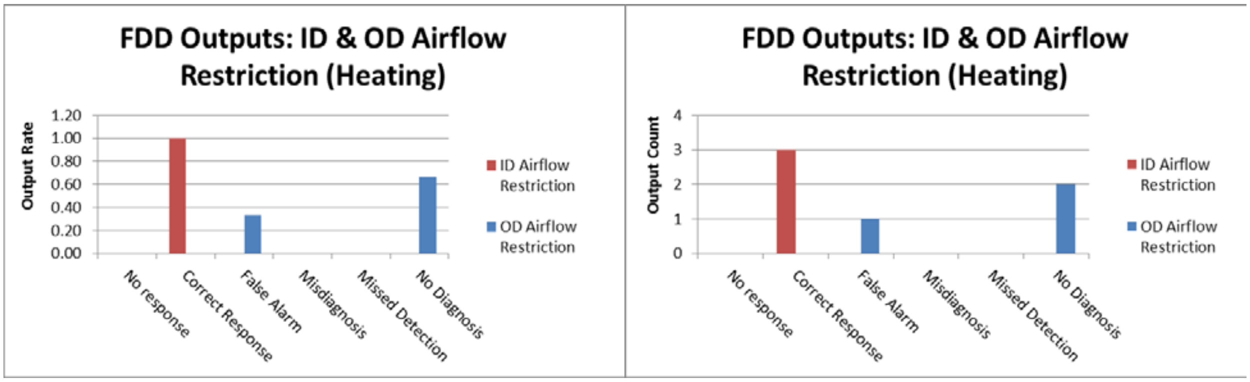

Table 50 – FDD Outputs: Single-Fault ID Airflow Restriction & Single-Fault OD Airflow Restriction, Heating Mode

Fault	FDD Test Unit	Number of Tests	Tests that Exceed Threshold	Sum of Total Outputs	Output	Output Rate	Output Count	ID/OD Test Chamber Conditions: Mild 80F/67F ID 80F OD		
							Test ID ->	36	37	38
							Fault Severity ->	Lo	Med	Hi
							Fault Threshold Exceeded?	Yes	Yes	Yes
ID Airflow Restriction	Unit X	3	3	3	No response	0.00	0	0	0	0
					Correct Response	1.00	3	1	1	1
					False Alarm	0.00	0	0	0	0
					Misdiagnosis	0.00	0	0	0	0
					Missed Detection	0.00	0	0	0	0
					No Diagnosis	0.00	0	0	0	0
							Test ID ->	39	40	41
							Fault Severity ->	Lo	Med	Hi
							Fault Threshold Exceeded?	No	Yes	Yes
OD Airflow Restriction	Unit X	3	2	3	No response	0.00	0	0	0	0
					Correct Response	0.00	0	0	0	0
					False Alarm	0.33	1	1	0	0
					Misdiagnosis	0.00	0	0	0	0
					Missed Detection	0.00	0	0	0	0
					No Diagnosis	0.67	2	0	1	1

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge

Figure 55. FDD Outputs: Single-Fault Low Charge & Single-Fault High Charge, Heating Mode

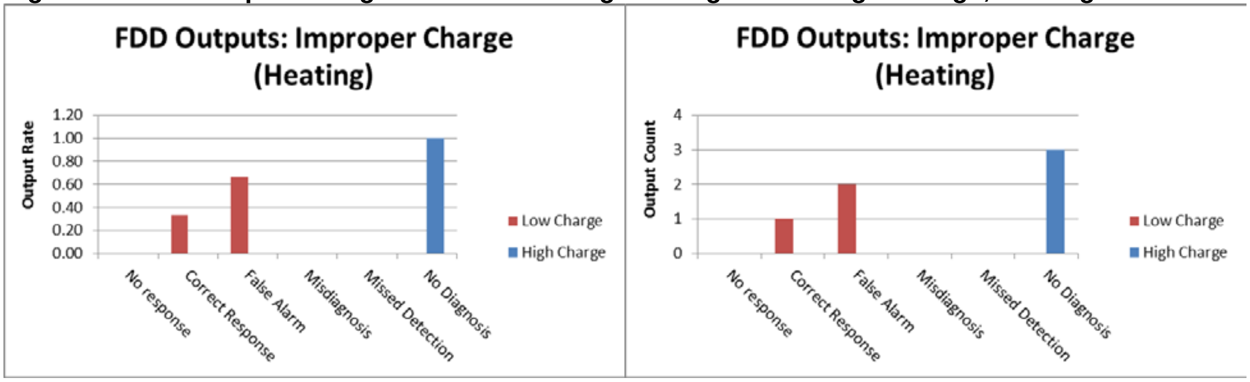

Table 51 – FDD Outputs: Single-Fault Low Charge & Single-Fault High Charge, Heating Mode

Fault	FDD Test Unit	Number of Tests	Tests that Exceed Threshold	Sum of Total Outputs	Output	Output Rate	Output Count	ID/OD Test Chamber Conditions: Mild 80F/67F ID 80F OD		
							Test ID ->	42	43	44
							Fault Severity ->	Lo	Med	Hi
							Fault Threshold Exceeded?	No	No	No
Low Charge	Unit X	3	0	3	No response	0.00	0	0	0	0
					Correct Response	0.33	1	0	0	1
					False Alarm	0.67	2	1	1	0
					Misdiagnosis	0.00	0	0	0	0
					Missed Detection	0.00	0	0	0	0
					No Diagnosis	0.00	0	0	0	0
							Test ID ->	45	46	47
							Fault Severity ->	Lo	Med	Hi
							Fault Threshold Exceeded?	Yes	Yes	Yes
High Charge	Unit X	3	3	3	No response	0.00	0	0	0	0
					Correct Response	0.00	0	0	0	0
					False Alarm	0.00	0	0	0	0
					Misdiagnosis	0.00	0	0	0	0
					Missed Detection	0.00	0	0	0	0
					No Diagnosis	1.00	3	1	1	1

Established fault threshold for analysis: >10% % air-side or refrigerant-side cooling impact, >10% total power impact, or >10% high charge

Conclusions

Promoting sustained, optimal performance in the world of HVAC presents big opportunities as well as monumental challenges in supporting the efficiency goals of California. In this, FDD continues to have a key role, with ample room for advancement. The understanding of FDD technologies has come a long way, but is still at the early stages. This study aimed to continue the understanding of FDD and the common/impactful faults they help address.

Overall, there exists a massive matrix of potential faults for the seemingly innocuous packaged rooftop unit air conditioner. These faults may come into existence in a variety of ways, made up of varying fault types, fault intensity/severity, fault combinations, system/component configurations, indoor/outdoor conditions, etc. This laboratory study focused on economizer, charge and airflow faults, anchored to one typical RTU heat pump, under OD conditions representative of California climate zones. The main areas for this study's findings include:

1. FDD performance for three units and RTU charge protocol under controlled, steady-state lab conditions under cooling mode operation
2. FDD performance for one unit under controlled, steady-state lab conditions under heating mode operation
3. FDD performance for one unit under economizer faults
4. The impacts of several common faults in single and multiple-fault scenarios

FDD performance for three units and RTU charge protocol under controlled, steady-state lab conditions under cooling mode operation.

- All tests
    - FDD unit 1
        - The only unit to give no response outputs
        - Highest count of correct responses
        - Highest count of false alarms, misdiagnoses, missed detections and no responses
        - Highest misdiagnosis rate by a slight margin
    - FDD unit 2
        - Highest correct response rate
        - Highest missed detection rate by a slight margin
    - FDD unit 3
        - The only unit with no missed detections
        - The only unit to give no diagnosis outputs
        - Highest false alarm rate
- Baseline tests
    - The RTU charge protocol established the nominal charge level of 11 pounds at the baseline test at 95°F OD. The RTU charge protocol continued to show proper charge at the 80°F and 115°F OD temperatures.
    - FDD unit 1

        - Highest count of correct responses and false alarms
            - Indicated false alarms simultaneously with correct responses for the baseline tests
    - FDD unit 2
        - Highest correct response rate, tied with RTU charge protocol
    - FDD unit 3
        - Highest rate of false alarms,
            - Indicated for the baseline tests at 80°F and 95°F OD temperatures
- Single fault tests
    - FDD unit 1
        - Highest count of correct responses, false alarms, and misdiagnoses
        - Highest count of missed detection outputs by slight margin, tied w/ unit 2
    - FDD unit 2
        - Highest correct response rate and missed detection rate
    - FDD unit 3
        - Only unit to give no diagnosis outputs
        - Highest rate of false alarms
    - RTU charge protocol had the highest misdiagnosis rate by slight margin
- Multiple fault tests
    - None of the FDD units could output a multiple simultaneous fault message, but were able to pick up on at least one of the three faults correctly.
    - FDD unit 1
        - Only unit to give no response outputs
        - Highest rate/count of missed detections
        - Equal misdiagnosis count with unit 3
    - FDD unit 2
        - Highest correct response rate/count
    - FDD unit 3
        - Only unit to give no diagnosis outputs
- Generally, FDD unit 1 produced roughly 3 times the amount of diagnostics than the other FDD technologies. The other FDD units generally had one output per test. However, FDD unit 1 had many instances of multiple conflicting messages. For example, indicating “undercharge” and “charge ok” simultaneously.
- For a few tests at the hot/dry OD ambient condition of 115F, the outdoor temperature measurements slightly exceeded 115F, which caused FDD unit 2 to be prevented from issuing diagnostics. The temperature was overridden to 115F.
- For high severity OD airflow restriction cooling mode tests, FDD units 1 & 3 could not accept the high side refrigerant pressure measurements. Their maximum values were instead used; FDD unit 1 maxes out at 555 psig, FDD unit 3 maxes out at 600 psig.

FDD performance under controlled, steady-state lab conditions for under heating mode operation

- Only one of the FDD units was able to perform diagnostics for the heat pump in heating mode, with the available measurements. The RTU charge protocol was not intended for heating mode operation.
- The FDD unit indicated a correct response for baseline no-fault operation.
- The FDD unit had correct responses for the ID airflow restriction tests, but gave false alarms and no diagnosis outputs for OD airflow restriction tests (no diagnosis had higher count/rate).
- The FDD unit had higher false alarm rates/counts than correct response rates/counts for low charge. The FDD unit issued no diagnosis outputs for the high charge faults.

FDD performance for various economizer faults

- FDD unit 4 was the only device that had economizer FDD capability
- Initiating damper movement with economizer test mode did not trigger FDD responses. Initiation of damper movement had to be done with manipulation of economizer control targets (high limit set point/minimum damper position) in order to solicit some FDD responses.
- FDD unit 4 diagnosed all but one of the economizer faults. Some registered instantly, others required initiation of damper movement via controls, and waiting of roughly 3 minutes for fault to register.
    - FDD unit 4 did not diagnose mechanical disconnect between outside air inlet damper and actuator

Fault Impacts: cooling & heating modes

- This project successfully explored the performance impact characteristics of the RTU under various fault conditions in cooling and heating mode. The data points serve to draw boundaries around the potential ranges of low/high impacts of faults. It remains to be seen what actual intensities of faults are predominant in the field. Variance in fault impacts is due to differences in ID/OD ambient conditions, cooling/heating operating mode, and cooling/heating capacity calculation method chosen.
- Single faults
    - ID airflow restriction
        - In cooling mode, the RTU was more resilient to ID airflow restriction at high OD temperatures. At 80°F OD, 42% ID airflow rate gave pre-coil-frosting condition vs a 25% ID airflow rate at 115°F OD.
        - In heating mode, compressor discharge temperatures can reach levels where refrigerant oil breakdown is a concern
        - Cooling mode up to 6% total power decrease, up to 49% gross cooling capacity decrease
        - Heating mode up to 63% total power increase, up to 43% gross heating capacity decrease
    - OD airflow
        - In cooling mode, the RTU is more resilient to OD airflow restriction at lower OD temperatures. To establish pre-failure conditions at 80F OD,

high side pressures can rise by 94%. At 115F, high side pressures can rise by 24%.
        - In cooling mode, compressor discharge temperatures can reach levels where refrigerant oil breakdown is a concern
        - Cooling mode up to 79% total power increase, up to 31% gross cooling capacity decrease
        - Heating mode up to 3% total power decrease, up to 38% gross heating capacity decrease
    - Low charge
        - Cooling mode up to 5% total power decrease, up to 14% gross cooling capacity decrease
        - Heating mode up to 6% total power decrease, up to 7% gross heating capacity decrease
    - High charge
        - In cooling mode, the RTU is fairly resilient to overcharge up to 30%, likely due to the TXV, but sees more pronounced effects in heating mode.
        - Low ambient cooling mode reliability impacts are unknown, since 80F was the lowest OD condition tested.
        - Cooling mode up to 4% total power decrease, up to 7% gross cooling capacity increase
        - Heating mode up to 47% total power increase, up to 7% gross heating capacity increase
    - Multiple fault: low ID/OD airflow and low charge
        - RTU demonstrated resilience in multiple fault intensity that it could absorb, while still running without failure.
        - In cooling and heating mode, compressor discharge temperatures can reach levels where refrigerant oil breakdown is a concern
        - Cooling mode up to 66% total power decrease (80°F OD), up to 76% gross cooling capacity decrease (95°F OD)
        - Heating mode up to 21% total power increase, up to 58% gross heating capacity decrease

Additionally, many noteworthy challenges were encountered during the equipment procurement and setup process:

- The factory economizer equipment was found to be appropriate for vertical ducting configuration. Separate equipment from a 3rd-party design was needed for horizontal ducted setup.
    - Incorrect relief air damper was specified by 3rd party (non-Title 24)
    - Damage occurred on the low-leakage gaskets for the outside air damper during shipment. Damage was determined to be cosmetic and did not impact the ability to seal effectively.

- The economizer module was received pre-wired incorrectly. Upon activation, the economizer FDD displayed an alarm.
- The economizer damper actuators were configured to operate in reverse: when call for 100% outside air was initiated, the outside air damper was closed in the 0% position

- The RTU was tagged as having been fully charged, but received with no refrigerant
  - The condenser was found to have two major leaks; repairs to condenser were deemed too extensive and would impact performance. A replacement condenser was procured and installed.
- Inconsistencies in check valve/filter-drier placement, and OD section TXV sensing bulb placement were identified in two versions of the refrigerant circuit diagram
- Large restriction was present in the original check valve, cause was unknown
- Transition ducting designed/fabricated by 3rd party required several iterations
  - Initial parts received were "mirror image" and incorrect
  - Design was based on original equipment in vertical ducting configuration, not horizontal
- Ongoing issues were observed in syncing FDD field measurement sensors to the analyzer
  - The data logging mode of the analyzer was unable to handle all of the field measurement sensors simultaneously
  - The analyzer's FDD mode was specified to be able to handle all field measurement sensors simultaneously, but signal loss was a frequent occurrence throughout testing
- The analyzer contained a port which appeared to be for connection to an AC adapter for power, but it was discovered later on from the manufacturer that this function was never enabled; the analyzer and all field sensors were meant to run off of battery power alone, so separate wiring needed to be rigged up for constant power to the battery terminals, to allow for ongoing testing without the need for handling the logistics of replacing batteries

The state of FDD technology today can assist in some key areas, but there are still many issues that reside outside the scope of FDD. It still remains to be seen what the valuation of FDD benefits currently is, and how far it can potentially go. This project has generated raw outputs of FDD performance, but additional steps to value these outputs needs to be pursued.

At this stage one cannot definitively assess what constitutes "good" FDD or "bad" FDD. It is cautioned to avoid the mindset of assuming that the goal of "good" FDD should be at/near 100% correct response count/rate (with 0% count/rate of other responses). This is an easy trap to fall into as it is an arbitrary, ideal notion, with no realistic foundation (You wouldn't make such a statement just as you would never make the statement that a "good" baseball player should be at/near a 100% batting average).

Next Steps

Great progress has been made in further understanding the world of FDD and fault impacts for HVAC, but more should be done through key industry platforms to refine the analysis methods and establish common, industry-adopted language and metrics. ASHRAE and the WHPA represent key industry platforms with which to continue the development of the analysis techniques and data that are still needed to fully understand FDD and fault impacts. The following activities are recommended:

- Establishment of a FDD technology "taxonomy", to make clearer the envisioned roles and functions of the FDD technology that is available/under development.
- A simulation methodology should be established (open for other competing simulation methods) to expand the possible fault scenarios that may be processed through FDD algorithms. Recommend further development of mechanisms like the Purdue FDD evaluator[11].
    - Update/extend analysis to give credit for symptom detection as well as fault detection/diagnosis.
    - Continuously leverage good data from existing lab and field measurements.
    - Position method to continuously learn from new lab and field measurements.
    - Should result in a single valuation metric (beyond the raw outputs), to differentiate FDD performance (similar to the "Wins above Replacement" metric in baseball).
- Establishment of a requirements criteria (a target), of those FDD functions that best enhance the needs of HVAC optimization EE program offerings (Quality Installation, Quality Maintenance, etc.). This list should leverage a performance-metric and/or a prescriptive list, as appropriate.

There is opportunity to build upon the current FDD requirements in California Title 24 building code through continued refinement of the language and adoption of a standardized certification test method. The current mandatory requirements language can be refined to better reflect the hierarchy of faults, to better represent economizer faults as opposed to the current matrixed scheme. The variation in content of certification submittals across the various economizer FDD manufacturers is currently unclear. ASHRAE SPC207P is a key group to work with, as their scope includes development of a lab test method for economizer FDD.

[11] http://www.purdue.edu/fddevaluator#info